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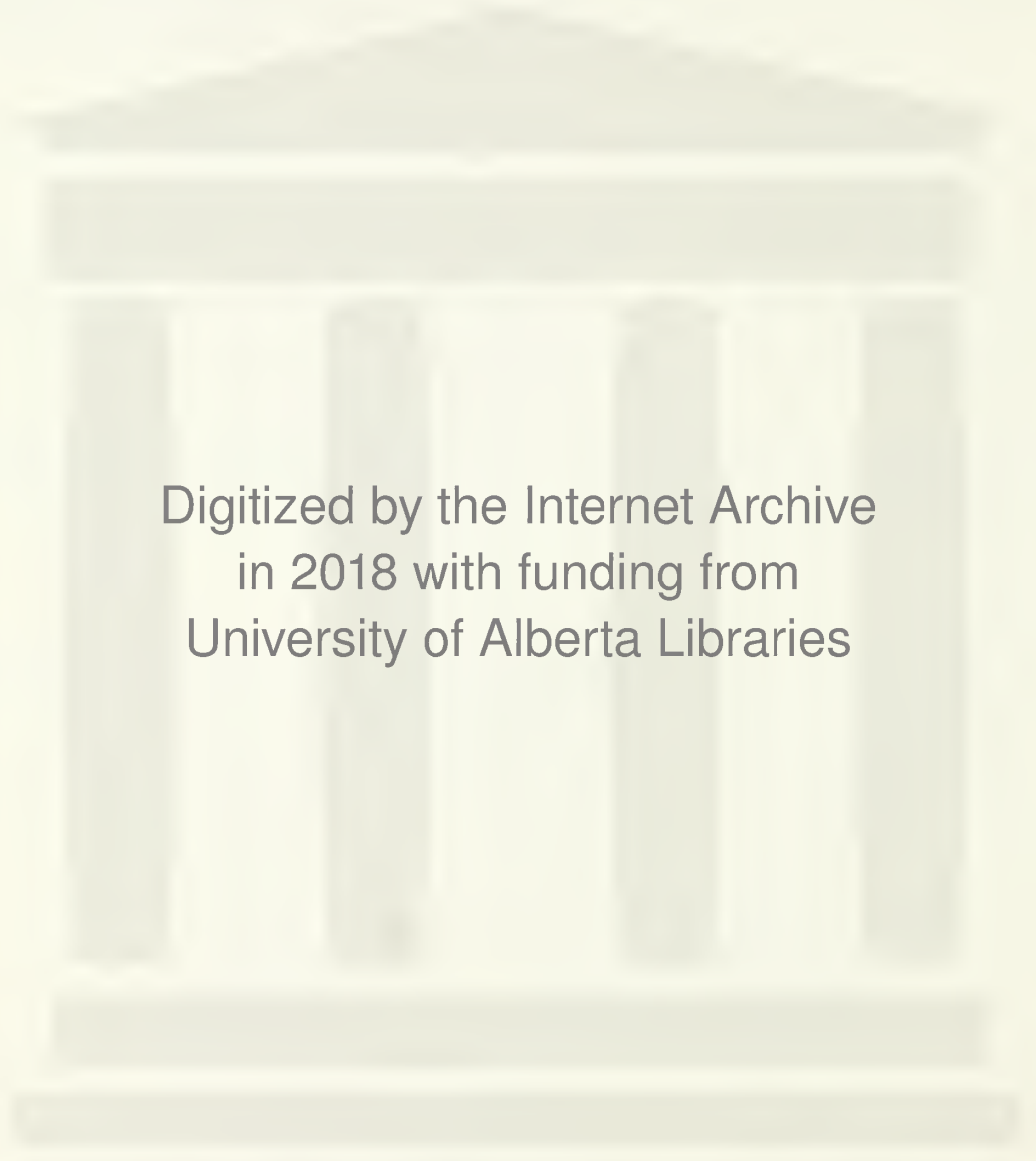
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TECHNOLOGY OF SOME ALBERTA SOIL SERIES

BY

MANFRED R. HAUSMANN
Dipl. Ing. ETH

A THESIS
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ABSTRACT

Previous research of physico-chemical nature in soil mechanics at the University of Alberta dealt with clayey soils, artificially modified in their exchange complex and salt concentration of the pore water.

This investigation is a technological study of soil modifications as produced by nature within a soil profile, in particular the B- and C-horizon materials.

Wetaskiwin, Camrose, Navarre and Angus Ridge soils were studied in detail. Additional valuable data on other soils were obtained from the Research Council of Alberta and available literature.

All tests were performed on remoulded material. Engineering tests determined Atterberg limits, grain size distribution, compaction, unconfined compressive strength, consolidation and swelling characteristics. Soluble salts and organic matter content were investigated by methods in use by engineers and soil scientists. Soil science tests gave information on the total exchange capacity, amount of adsorbed Na^{+}, K^{+}, Ca^{++} and Mg^{++}, electrical conductivity of pore water and relative amounts of the major clay minerals montmorillonite, illite and kaolinite.

With a few exceptions, no general trend in variation of properties of B- and C-horizon soils was observed. However, it was found that considerable differences exist within a soil profile and these may well be significant to the highway engineer. The total exchange capacity proved to be an important fundamental soil property, related to many engineering soil characteristics. An osmotic interpretation of consolidation test results is felt to be more informative for homionic than natural soils.

The clay mineral montmorillonite seems to have a pronounced effect on soil properties. Re-evaluation of previous results suggests a correlation of effective friction angle of Edmonton clay and the distance between basal planes of montmorillonite.

It is recommended that further research should investigate the effective salt content in a soil in regard to various engineering properties, the reaction of B- and C-horizon to different stabilizing agents and the role of clay minerals of the expanding lattice type in a soil.

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Osmotic pressure would be developed also when the free movement of the solute particles is restricted not by a membrane but by forces of adsorption and electrostatic attraction.

Parent Material: See C-horizon.

Pedology: The science which deals with soils, their origin, character and utilization.

Soil Profile: Succession of zones or horizons beginning at the surface that have been altered by normal soil forming processes of which leaching and oxydation have been particularly important.

Soil series: Basic unit of pedological soil classification system.

Solum: The upper part of the soil profile, above the parent material, in which the processes of soil formation are taking place. Includes A- and B-horizons.

Total Exchange Capacity: The quantity of cations adsorbed by the clay minerals in milliequivalents per 100 grams of air dried soil.

GLOSSARY OF SYMBOLS

A	A-horizon.
a.d.s.	air dry soil.
Ar.	Angus Ridge.
B	B-horizon.
C	C-horizon.
C	soluble constituents in p.p.m.
Ca	Calcium.
Cam	Camrose.
ΣCat.	sum of cations Na^+, K^+, Ca^{++} and Mg^{++} in me/100 grams.
C_c	compressive index.

c_v	coefficient of consolidation.
D	dilution of soil water mixture.
d_{max}	maximum density.
e	void ratio.
EC	electrical conductivity.
G_S	specific gravity.
I	integrated area.
I_f	flow index (slope of flow line on semi-log paper).
I_t	toughness index.
I_q	unconfined compressive strength index.
k	permeability.
K	Potassium.
me	milliequivalent.
Mg	Magnesium.
N	normal.
Na	Sodium.
Nv.	Navarre.
OMC	optimum moisture content.
P	percentage of soluble constituents by dry weight.
PR	penetration resistance = unconfined compressive strength measured by means of pocket penetrometer.
q_u	unconfined compressive strength.
S.C.	salt content, equal to ΣCat.-TEC.
SP	swelling potential.

t_{100}	time required to reach theoretical 100% consolidation.
tan B	slope of flow line on double log paper.
TEC	total exchange capacity.
Wkn.	Wetaskiwin.
w	moisture content.
w_L	liquid limit.
w_p	plastic limit.
w_S	shrinkage limit.
ZAV	zero air void curve.

CHAPTER I

INTRODUCTION

The title of this thesis incorporates two terms not commonly used in soil mechanics: 'Soil Technology' and 'Soil Series'.

Soil technology has been defined by Lambe (1957) as the applied science which treats the geological history and the composition of soil and the influence of these two factors on the engineering behaviour of soil. Soil technology not only examines the physico-chemical nature of the soil components, but considers also the arrangement of individual particles and the interactions among them. Therefore a technological study of soil, as represented by this thesis work, has to draw upon soil science, colloid chemistry, mineralogy and geology as well as upon engineering.

The study of physico-chemical phenomena in soil mechanics has received considerable attention in previous research at the University of Alberta. In 1950 the effect of direct current on characteristics of certain clay types was studied, followed by detailed investigations concerning electro-osmotic stabilization of soils (Fowler, 1950; Spencer, 1951; Hughes, 1953). In 1960 P.A. Thomson successfully altered the cation exchange complex of Lake Edmonton clay and tested some of the engineering properties of the obtained modifications. This work was continued by Hamilton (1961) and Locker (1963) and showed that the properties of highly plastic clay are significantly affected by the nature of the cation exchange complex and the

concentration of salts in the pore water. The soil properties examined included Atterberg limits, specific gravity, grain size distribution, permeability, consolidation, swelling and strength properties. The study of homionic soils with various salt concentration in the pore water culminated in the investigations of the shear strength parameters by S. Thomson (1963).

So far studies of physico-chemical nature at the University of Alberta have been carried out mainly on artificially modified soils and it seems desirable that these test results should be supplemented by an investigation of soil modifications as produced by nature.

Soil science has shown that weathering and soil-forming processes give rise to a gradual differentiation of layers within a parent soil (see e.g. Millar, Turk and Foth, 1958). The surface layer, or A-horizon, contains an accumulation of organic matter and is characterized by the leaching out of certain soil constituents. The B-horizon is a zone where material removed from the overlying layers is deposited. The parent material is referred to as C-horizon. Each horizon is subdivided into further layers as necessary. The percolating rain water tends to leach the soluble salts into the C-horizon and therefore in the moderately to well-drained soils the A- and B-horizons are relatively salt free.

Soil profiles of similar characteristics are grouped by the pedologist in so-called soil series and given a name, usually after the area where the specific series predominates or first has been discovered.

In spring 1963 it was decided to start a testing program to determine the properties of the various soil modifications as formed by

nature on the same parent material. The purpose of this investigation was postulated to consist of:

1. Comparing characteristics of the B- and C-horizon of several Alberta soil series and evaluate the engineering significance of eventual differences.

2. Trying to explain differences in their properties based on findings of previous research on artificially treated homionic clays.

An initial testing program was set up in cooperation with Dr. S. Thomson from the Department of Civil Engineering and Dr. S. Pawluk from the Department of Soil Science at the University of Alberta and later extended by the author. The initial laboratory work was carried out in summer 1963 under the auspices of the Research Council of Alberta, through the Alberta Cooperative Highway Research Program, represented by Mr. B.P. Shields, Head of the Highways Division and continued throughout the academic year 1963/64.

CHAPTER II

REVIEW OF SOME FINDINGS OF SOIL SCIENCE

2:1 Soil Development

For the soil scientist, soils are not merely an accumulation of debris, resulting from decay of rock and organic material. Soils are developed in a constructive as well as destructive process on two classes of parent materials (Millar, Turk and Foth, 1958),

> "(1) partially decomposed plant substance (organic material); and (2) rocks and minerals (mineral material). Igneous as well as sedimentary and metamorphic rocks can serve as a mineral parent material. Sedimentary rocks include glacial till, alluvial and wind-transported material."

Examples of destructive soil-forming processes are weathering and microbial decay of organic residues; but the formation of new materials, such as certain clays, and the development of characteristic layer patterns are synthetic in nature (Buckman and Brady, 1962).

2:2 Soil Profile

In soil science, 'soil' is defined as that part of the earth surface that is utilized by the growing plant, and may vary from a few inches to several feet in thickness (Alberta Soil Survey, Report No. 14, 1947). A vertical cross-section of this layer is called the soil profile. The development of horizons in the soil profile is the result of soil-forming forces working for long periods of time. The nature of the horizons

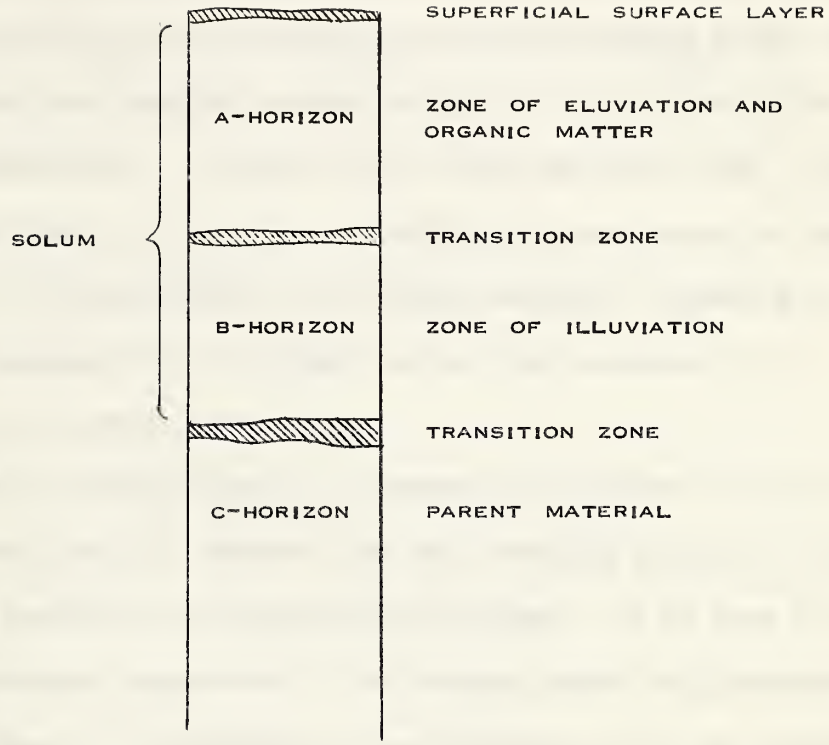


FIGURE 1. – SCHEMATIC DIAGRAM OF SOIL PROFILE.

in a profile and the intensity of their development depend on many factors; varying topography, climate, vegetation, activity of soil micro-organisms as well as different mineral composition of the parent material form many kinds of soil profiles and no two horizons are ever exactly alike. Most profiles, however, are generally characterized by two or more of the following horizons (FIG. 1, compare Millar, Turk and Foth, 1958, p.39):

(1) The surface layer, or A-horizon, contains an accumulation of organic material. It is subdivided into further sections, depending on the degree of decomposition of organic matter and leaching out of original soil constituents.

(2) The horizon of accumulation or illuvation is referred to as B-horizon, a layer where material removed from the overlying horizons is deposited.

(3) The parent material is designated as C-horizon; it is more or less the same material as existed on the surface before soil-developing processes began. In moderately to well-drained soils the C-horizon may contain an accumulation of soluble salts leached out from the A- and B-horizon by percolating rain water (Alberta Soil Survey Report No. 21, 1962, p.59).

All these horizons may not be present in every soil due to such factors as insufficient rainfall or lack of vegetation. In the field, colour, structure and salt content are the most important properties with regard to the pedological identification of the various horizons.

2:3 Soil Classification

In 1960 the soil survey organizations across Canada accepted a new National Taxonomic System of Soil Classification. The taxonomic system

places soils in categories at different levels of generalization on the basis of their internal characteristics. Six categories are used. According to A. Leahey (1961) these are:

Category 1: The soil type: this is a subdivision of the soil series based on the texture of the surface soil; hence its retention in the classification system as the lowest category is perhaps more a matter of traditional use than logic.

Category 2: The soil series: this is the basic unit of classification in the system since it is the natural body in the definition of soil from a pedologist's viewpoint; the series in some soil survey reports is named a "member" or an "associate".

Category 3: The soil family: this is a grouping of series belonging to the same subgroup on the basis of some important characteristics in the parent material; this category has not as yet been widely used in Canada.

Category 4: The subgroup: the subgroup is analogous with the types of profiles long recognized in Canada.

Category 5: The great group: this is a grouping of the subgroups on the basis of profile similarities.

Category 6: The order: the great groups are organized into orders on the basis of major profile similarities.

Some 1800 soil series have been identified in Canada to date and can be placed in about 100 subgroups, 23 great groups and 6 orders.

In TABLE I a classification of the soils of the Edmonton Sheet (Alberta Soil Survey Report No. 21, 1962) as related to parent materials is given. It illustrates the wide variety of agricultural soil types which can be found in the Edmonton area.

TABLE I

CLASSIFICATION OF THE SOILS OF THE EDMONTON SHEET [83-M] AS RELATED TO PARENT MATERIALS

[FROM ALBERTA SOIL SURVEY REPORT NO. 21]

Order	Great Group	Sub-group	Parent Material						
			Glacial Till	Alluvial Lacustrine	Lacustrine	Alluvial Aeolian	Outwash	Residual	Pitted Deltaic
Chernozemic	Black	Orthic Black	Didsbury Beaverhills Elnora	Penhold	Navarre	Peace Hills Irma	Ferintosh		
		Eluviated Black	Angus Ridge	Ponoka	Malmo				
		Gleyed Black		Penhold Meadow		Peace Hills Meadow			
		Eluviated Gleyed Black	Angus Ridge Meadow	Ponoka Meadow					
	Dark Grey	Orthic Dark Grey	Falun	Rimbey	Mico				Winterburn
Solonetzic	Alkali Solonetz	Black	Whitford						
	Solonetz	Black			Duagh				
	Solodized Solonetz	Black	Camrose Kopernick Killam	Armena	Wetaskiwin Gadsby			Kavanagh	
		Dark Grey	Thorsby						
		Grey Wooded	Dnister		Ministik			Kawood	
	Solod	Black	Daysland	Kapona	Botha				
Podzolic	Grey Wooded	Orthic Grey Wooded	Cooking Lake Breton	Tolman	Maywood	Culp		Modeste	Glory
		Dark Grey Wooded	Uncas	Holburn	Macola	Leith			Carvel
	Podzol	Minimal Podzol					Edwand		
Gleysolic	Meadow	Peaty Meadow		Codner	Prestville				
		Saline Meadow			Navarre				
	Eluviated Gleysol	Low Humic	Demay						
*Regosolic	Regosol	Orthic Regosol			Bittern Beach Sand				

*Dune Sand is of aeolian deposition and Alluvium is primarily of alluvial deposition.

CHAPTER III

SOIL SAMPLING AND TESTING PROGRAM

3:1 Sampling

In cooperation with Dr. S. Pawluk (Dept. of Soil Science) and Dr. S. Thomson (Dept. of Civil Engineering), four Alberta soil series were chosen for detailed investigations viz. Wetaskiwin, Camrose, Navarre and Angus Ridge. They represent two solonetzic and two chernozemic soils, formed either on till or lacustrine parent material. A variation in salt content was obtained by sampling soil from both the B- and C-horizons of one soil profile.

The Wetaskiwin (Wkn.) and Camrose (Cam.) series both belong to the solonetzic soil order but were formed on different parent materials: Camrose on glacial till, Wetaskiwin on lacustrine soils (see TABLE I). Solonetzic soils have developed from saline parent material or under the influence of saline waters. The parent material is of dominant influence in the development of these soils. A tough, finely textured B-horizon, which usually breaks down into columnar structures or blocky aggregates, is characteristic of this order. Solonetzic soils usually have an exchangeable base status in which the ratio of calcium to magnesium is one or less, or which has more than 15% exchangeable sodium (Alberta Soil Survey Report No. 21, 1962).

Angus Ridge (Ar.) and Navarre (Nv.) are members of the chernozemic

soil order. A- and B-horizons are usually well drained and free of soluble salts. These soils have dark coloured mineral-organic surface horizons and brownish, usually prismatic, subsurface and usually non-saline horizons lying on calcareous parent material. The cationic ratio of calcium to other ions is significantly greater than one. Test results on these series were later supplemented by data for Malmo clay, obtained in another project of the Alberta Research Council. This soil belongs to the same subgroup as Angus Ridge but was developed on lacustrine parent material (like Navarre).

Sampling of soil was first done in May 1963. For some tests an additional amount of soil was found to be necessary in July. In both cases the soil was sampled at exactly the same place.

3:2 Comments on Testing Program

The tests performed to evaluate engineering properties of the soils included:

Atterberg limits
Specific gravity
Grain size distribution (Hydrometer method)
Compaction
Swelling potential
Unconfined strength
Consolidation

Further tests were performed in order to determine the salt content and amount of organic matter by means of simplified physico-chemical methods as adopted by engineers.

Using standard soil science procedures the following basic soil properties were investigated:

Grain size distribution (pipette method)
Total exchange capacity and exchangeable cations
Salt content
Organic matter (carbon test)
Clay minerals (X-ray method)

It is of importance to notice, that all tests were performed exclusively on remolded soil. Soil strength characteristics were measured by means of unconfined compression tests on compacted samples and not as initially planned by using triaxial procedure on undisturbed samples. This was necessitated due to the time required for triaxial testing.

All tests were performed in the laboratories of the Departments of Civil Engineering and Soil Science of the University of Alberta with exception of the X-ray analysis, which was provided by the Research Council of Alberta.

CHAPTER IV

ENGINEERING TESTING PROCEDURES AND RESULTS

4:1 Standard Tests

Standard engineering tests were performed to classify the soils for engineering purposes and evaluate their major properties in regard to highway construction problems.

4:1:1 Atterberg Limits

Determination of the liquid limit by the standard method was generally performed according to ASTM D 423-54T. The soil was soaked for several hours before being tested. At least six trials were made on one sample. At least three points on the flow line were obtained close together above and three points below the liquid limit. Materials and apparatus were as specified by ASTM, except that the SOILTEST grooving tool (Casagrande type) was used. The method used to determine the plastic limit was ASTM D 424-54T. The shrinkage limit test was performed according to ASTM D 427-39.

The test results are given in TABLE III. The values for the liquid limit, w_L, plastic limit w_p, and shrinkage limit w_S are supplemented by the plasticity index I_p (equal to $w_L - w_p$) flow index I_f (slope of the flow curve on a semilogarithmic plot), toughness index I_t (equals the ratio I_p/I_f) and tan B (slope of flow curve on double logarithmic paper). The results are plotted on Casagrande's Plasticity Chart in FIGURE 2.

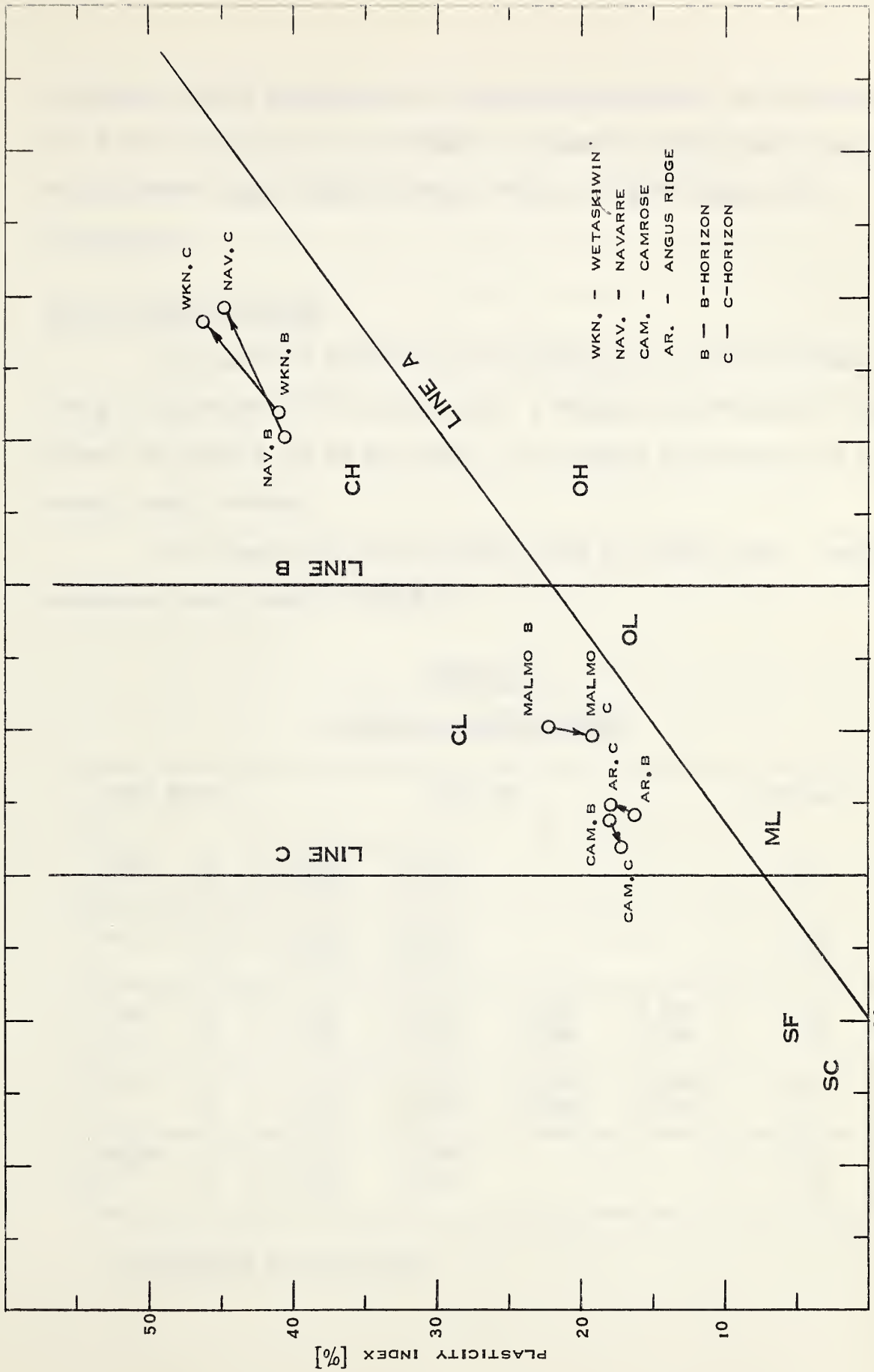


FIGURE 2. - PLASTICITY CHART.

According to USCS (Unified Soil Classification System), the Wetaskiwin and Navarre soils may be classified as inorganic highly plastic clay, while Camrose, Angus Ridge and Malmo soils are silty clays of low plasticity.

4:1:2 Specific Gravity

The specific gravities were determined as outlined by Lambe (1951) using a pycnometer of 500 ml capacity. A vacuum of approximately 0.84 kg/cm^2 was applied for 2½ to 4 hours. Air removal was intensified by using a small vibrator.

The results of the individual tests are given below. Average values are also listed in TABLE II.

TABLE II

SPECIFIC GRAVITY RESULTS

SOIL TYPE		Test No. 1	2	3	4	Average
Wkn.	B	2.709	2.720			2.71
	C	2.658*	2.716			2.71
Nv.	B	2.704	2.691			2.70
	C	2.727	2.709			2.72
Cam.	B	2.723	2.679	2.694	2.698	2.70
	C	2.700	2.703	2.699	2.701	2.70
Ar.	B	2.670	2.713	2.698	2.690	2.69
	C	2.705	2.678	2.720	2.720	2.71
Malmo	B	2.663	2.686			2.67
	C	2.699	2.697			2.70

* Considered to be in error.

4:1:3 Grain Size Distribution (Hydrometer Method)

With the exception of some variation in the pre-treatment, the standard procedure of the Department of Civil Engineering was used. It is generally the same as given in ASTM D 422-54T. Twenty-five or thirty cm^3 of Calgon 6% were used as a dispersing agent. The pre-treatment involved boiling of the sample for 2 to 3 hours in 6 or 12% H_2O_2 - solution. The treatment of material from B- and C-horizon of each soil series was strictly the same.

The hydrometer had been calibrated previously using the method outlined by Lambe (1951). Immersion correction, meniscus correction, temperature correction and Calgon correction were introduced as found in previous research.

A graphical presentation of the grain size curves for each soil may be found in Appendix A. The percentage finer than 0.002 mm (upper limit of clay sizes, M.I.T. scale) and finer than 0.05 mm is given in TABLE III.

4:1:4 Compaction

Two types of compaction tests were performed. The Standard Proctor compaction was used in connection with the evaluation of the swelling potential. Samples for the unconfined compression tests were formed by means of the Miniature Harvard compaction apparatus and this gave further information on the moisture-density characteristics of the soils.

Test results for Wetaskiwin, Navarre, Camrose and Angus Ridge soils are presented graphically in FIG. 3a and 3b. FIGURES No. 4 and 5

TABLE III

SUMMARY OF ENGINEERING CLASSIFICATION

TEST RESULTS

SOIL TYPE		W_L %	W_p %	I_p %	W_S %	I_f	I_t	tan B	G_S	Grain Size Analysis (Hydrometer) % Finer than 0.05 mm	0.002 mm	Activity 1)
Wkn.	B	61.7	20.7	41.0	9.5	11.1	3.69	0.068	2.71	86	51	.89
	C	68.2	22.1	46.1	7.9	15.9	4.29	0.098	2.71	82	60	.84
Nv.	B	60.2	20.7	40.5	9.4	10.1	4.03	0.069	2.70	85	49	.92
	C	69.2	24.4	44.8	12.5	11.8	3.82	0.072	2.72	87	62	.79
Cam.	B	33.7	15.7	18.0	13.6	5.7	3.14	0.071	2.70	56	17	1.56
	C	31.8	14.6	17.2	20.3	9.3	1.84	0.122	2.70	56	14	1.91
Ar.	B	34.3	17.9	16.4	13.7	4.7	3.50	0.058	2.69	57	12	2.34
	C	34.9	16.9	18.0	15.0	5.3	3.38	0.064	2.71	58	12	2.57
Malmo	B	40.2	18.1	22.1	12.6	9.0	2.45	0.106	2.67	64	31	.85
	C	39.5	20.1	19.4	19.1	9.7	1.98	0.100	2.70	83	24	1.02

1) Activity value as proposed by Seed et al, 1962

$$A = \frac{I_p}{(\% \text{ Finer .002 mm} - 5)}$$

allow a further comparison of Standard Proctor and Miniature Harvard test results. Test results are also summarized in TABLE IV, including Malmo soils.

(i) Standard Proctor Compaction

These tests were performed with the standard field apparatus as described by AASHO Designation T99-57. Generally fresh soil was used; in one case part of the soil was re-used in an attempt to get additional points of the compaction curve. All samples were soaked at their molding water contents for at least twenty-four hours before testing.

(ii) Miniature Harvard Compaction

Testing equipment and procedure used was as suggested by ASTM (1958), p.133. Each of five layers was compacted by 10 tamps with a 20 lb. spring tamper.

4:1:5 Swelling

In order to be able to compare the swelling of the soils under investigation with other research data, it is necessary to choose standard condition of placement and test. The procedure adopted is that proposed by Seed (1962) which uses Standard Proctor compaction procedure. The samples are formed in a lucite ring, built into a split type mold, as shown on PLATE 1A. The soils are compared by determining the amount of expansion that each soil would exhibit if it were soaked under a 1-psi surcharge after being compacted to maximum density at optimum water content in the Standard AASHO compaction test. In other words, the swelling

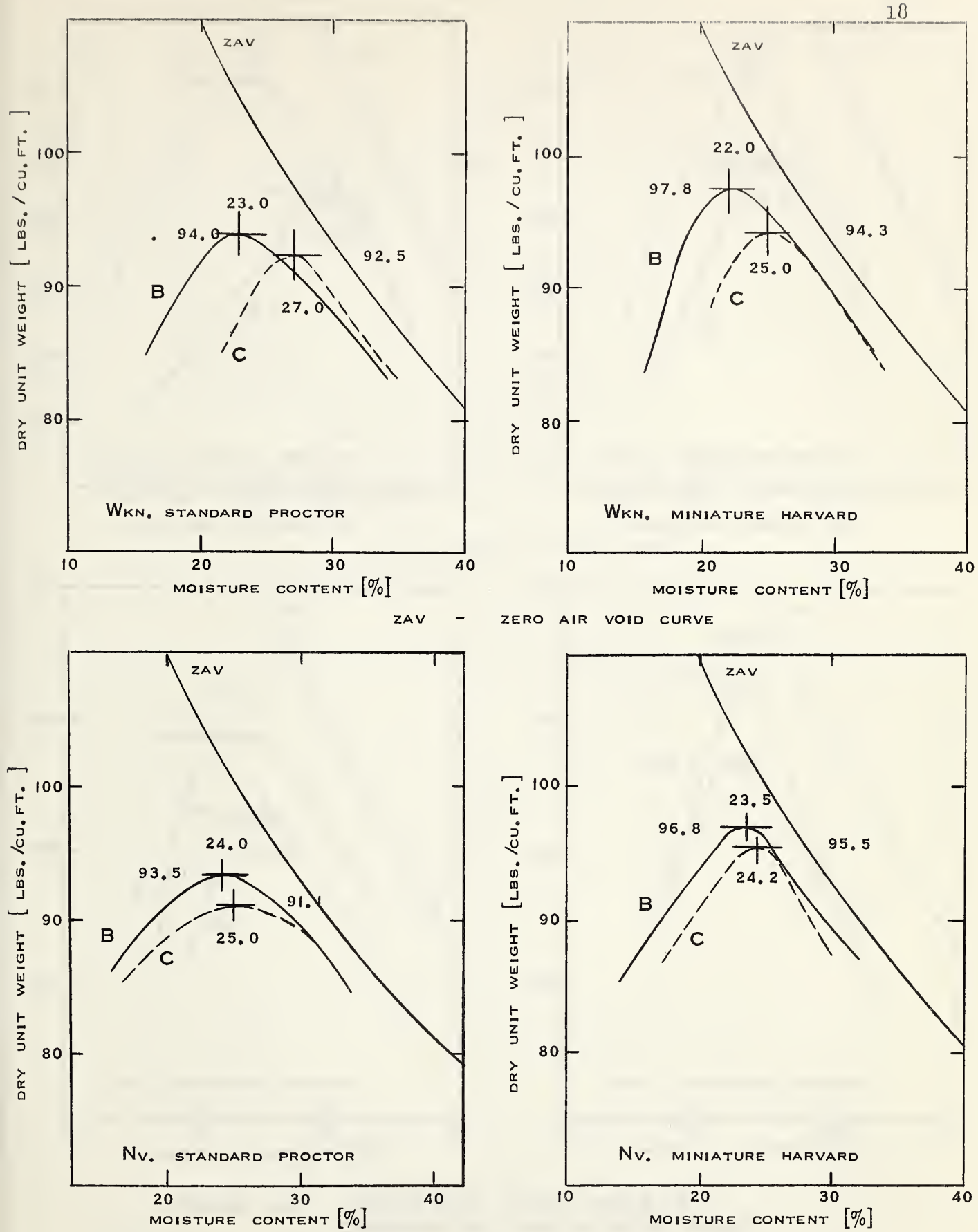
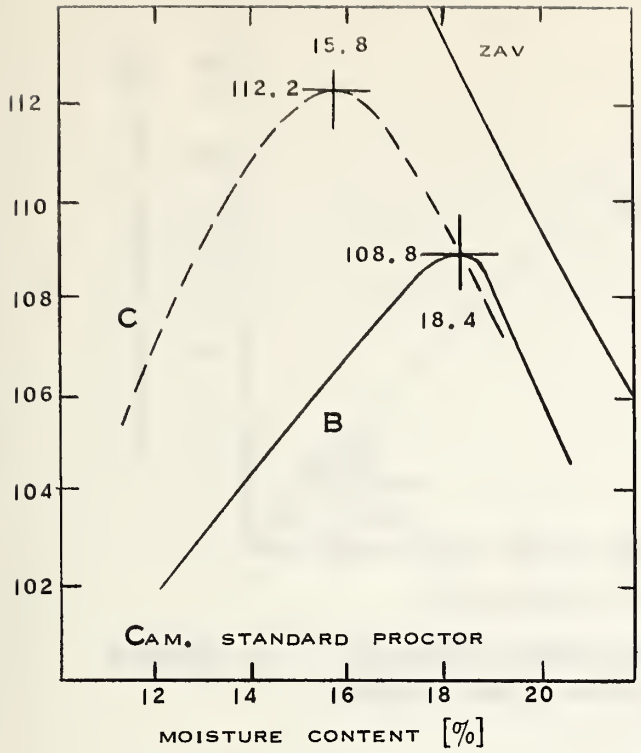
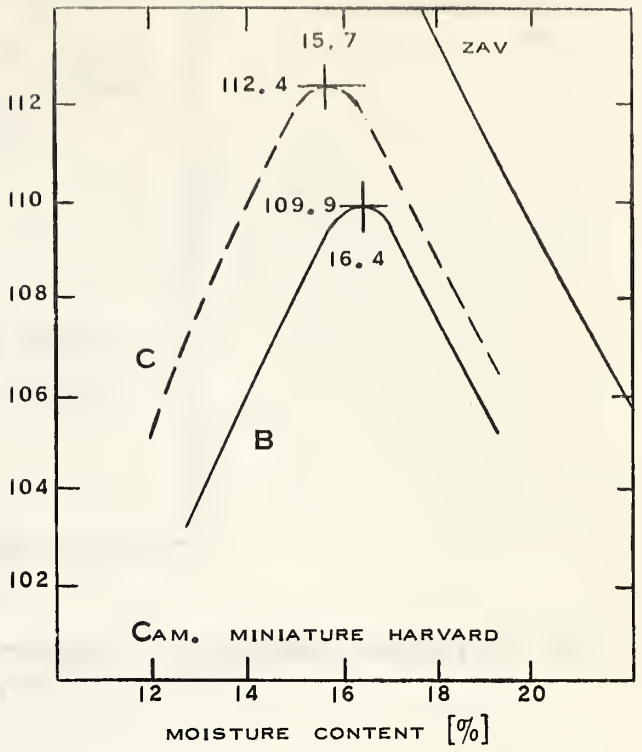
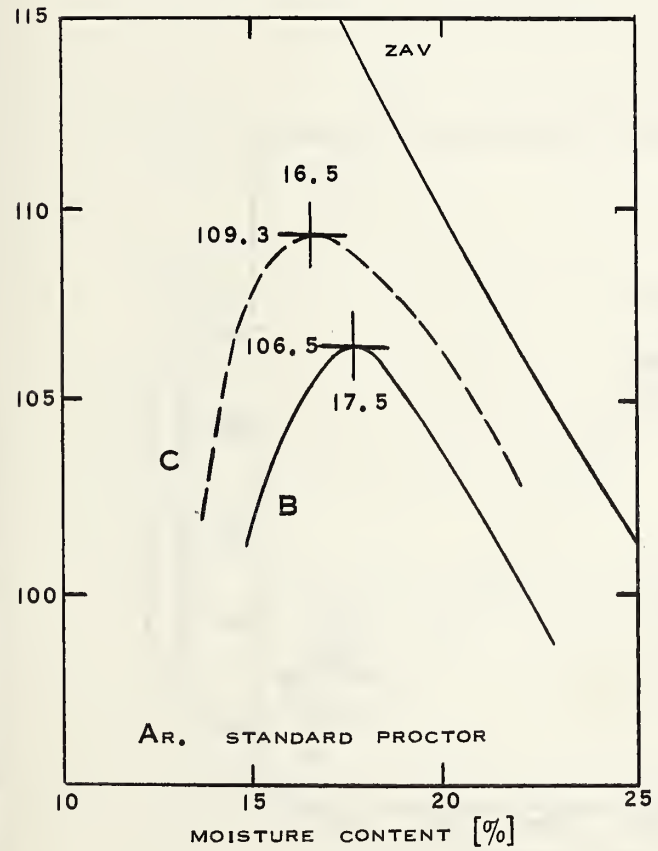


FIGURE 3A.– COMPACTION TEST RESULTS,
WETASKIWIN AND NAVARRE SOILS.





ZAV - ZERO AIR VOID CURVE



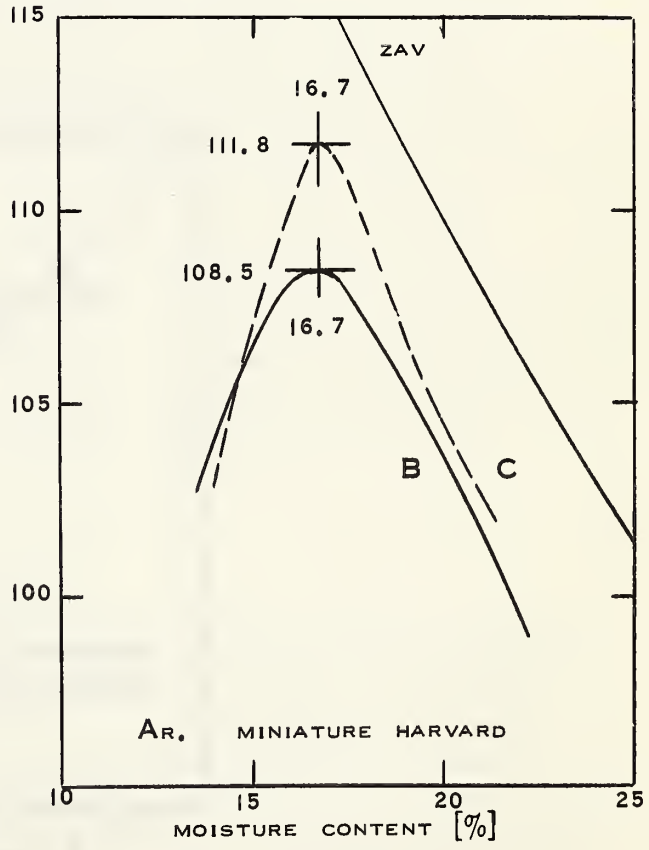


FIGURE 3B. – COMPACTION TEST RESULTS, CAMROSE AND ANGUS RIDGE SOILS.

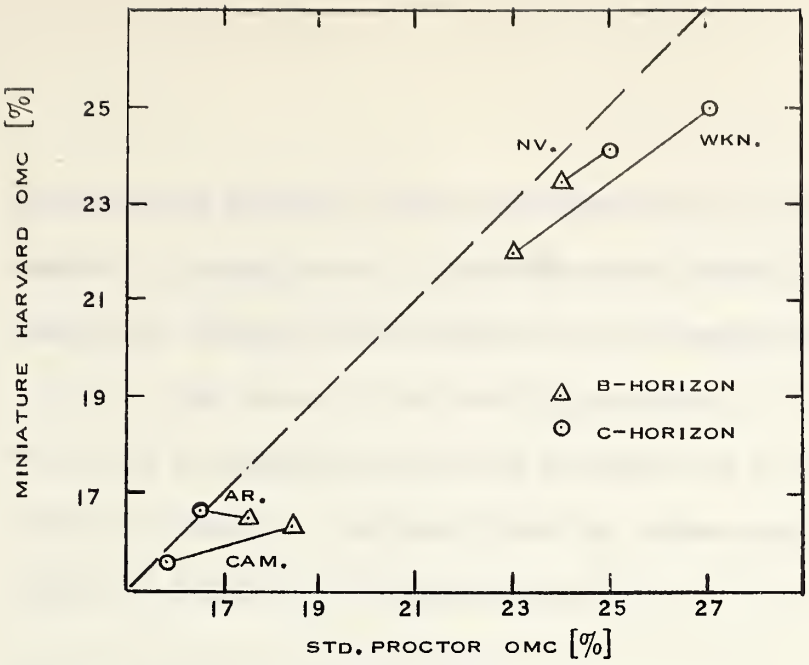


FIGURE 4. – OPTIMUM MOISTURE CONTENT , STANDARD PROCTOR VS. MINIATURE HARVARD TEST.

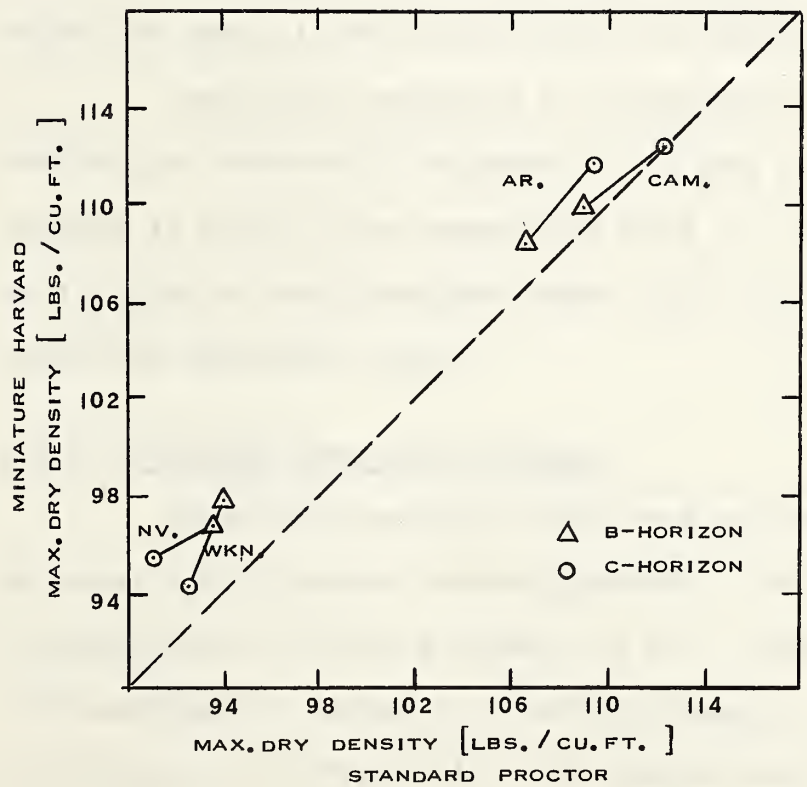


FIGURE 5. – MAXIMUM DRY DENSITY , STANDARD PROCTOR VS. MINIATURE HARVARD TEST.

potential is defined as the percentage swell of a laterally confined sample on soaking under a 1-psi surcharge after being compacted to maximum density at optimum water content in the Standard AASHO compaction test.

The value of the swelling potential is shown graphically in FIG. 6a-d in connection with the presentation of compaction and penetration test results. Pertinent data are summarized in TABLE IV. Further numerical data may be found in Appendix B.

4:1:6 Penetration Resistance

The unconfined compressive strength of the soil as compacted and after swelling was measured by means of the Soiltest pocket penetrometer. The results are plotted in FIG. 6a-d; each point represents an average of 10 penetration tests, 5 at the bottom and 5 at the top of either the sample in the Proctor mold or in the swell test ring.

Penetration resistance at optimum moisture content before swelling and penetration resistance of the same sample after soaking and swelling is listed in the summarizing TABLE IV. Penetration results are also plotted on semi-logarithmic paper (FIG. 7-10) in connection with unconfined compression tests.

4:1:7 Unconfined Compressive Strength

Unconfined compression tests were performed on samples compacted by means of the Miniature Harvard apparatus. Test samples have a length of approximately 2.8" and a diameter of 1.3". Wetaskiwin soil samples were compressed to failure in a Soiltest frame at a constant rate of strain of 0.05"/min. or 1.8%/min. All other samples were brought to failure

using a portable hydraulic unconfined compression apparatus, also manufactured by Soiltest Ltd. The average rate of strain varied from about 6 to 25%/min. as estimated from measurements of time to failure and strain at failure.

In the following figures (FIG. 7, 8, 9 and 10) unconfined compressive strength is plotted versus water content and degree of saturation.

TABLE IV gives the unconfined compressive strength, q_u, at optimum moisture content (Miniature Harvard compaction test) and the slope of a straight line approximating the relationship q_u versus moisture content above OMC. This slope has been called the Unconfined Compressive Strength Index and designated by I_q. It has been calculated as

$$I_q = \frac{(w \text{ for } q_u = 10 \text{ psi}) - (w \text{ for } q_u = 30 \text{ psi})}{\log 30 - \log 10}$$

q_u measured in psi.

Numerical strength data may be found in Appendix C.

For qualitative comparison with the unconfined compressive strength results, penetration resistances also are plotted versus moisture content on a semi-logarithmic plot (FIG. 7b, 8b, 9b and 10b).

4:1:8 Consolidation

The specimen preparation and testing procedure used for this program are essentially the same as outlined by Lambe (1951). All tests were performed on remoulded samples, starting at a moisture content near liquid limit.

For Navarre and Camrose soils a Farnell Consolidometer was used, while Wetaskiwin soils were tested in a Wykham Farrance Bench Model

Consolidometer (see PLATE 1). The diameters of the samples formed were 2.55 and 2.5 inches, respectively. The initial load applied resulted in a pressure of about 0.100 kg/cm^2 or less and was doubled every twenty-four hours to a maximum of 7.82 kg/cm^2. The rebound curve was obtained by decreasing the load with a ratio 4:1. No consideration was given to possible errors due to compressibility of filter paper or side friction, since they are believed to be small and because this investigation is mainly concerned with relative differences between B- and C-horizon soils.

The soil was prepared with distilled water. Measurements of electrical conductivity of the pan water after the tests indicated that soil salts had been dissolved during the experiment. Pertinent consolidation test results and conductivity measurements are reported in TABLE V. The consolidation curves are presented in FIG. 11. FIGS. 12 and 13 describe the variation of the coefficient of consolidation and permeability over the last three load increments.

4:2 Special Tests

Special tests were used to determine content of salts and organic matter contained in the soil samples. The properties mentioned under this heading are of physico-chemical nature and have been measured by procedures originally used in agriculture and soil science, subsequently adopted and modified by engineers.

4:2:1 Salt Content

(i) Determination of salt content by weight

The Earth Manual (1960) describes a method for determining

TABLE IV

SUMMARY OF COMPACTION, SWELLING AND STRENGTH TESTS

SOIL TYPE		Std. Proctor W opt. %	Std. Proctor d max lbs/ft^3	Min. Harvard W opt. %	Min. Harvard d max lbs/ft^3	SP %	PR at d max as comp. kg/cm^2	PR at d max as soaked kg/cm^2	q_u W opt. PSI	I_q
Wkn.	B	23.0	94.0	22.0	97.8	8.90	4.5	0.8	46	16.1
	C	27.0	92.5	25.0	94.3	5.50	2.6	1.0	35	15.5
Nv. 1)	B	24.0	93.5	23.5	96.8	2.70	2.95	1.4	29	16.1
	C	25.0	91.1	24.2	95.5	5.0	3.25	0.9	34	15.9
Cam.	B	18.4	108.8	16.4	109.9	.62	1.6	1.35	23	10.9
	C	15.8	112.2	15.7	112.4	.87	2.75	1.6	25	9.0
Ar.	B	17.5	106.5	16.7	108.5	.66	2.7	1.85	25	9.4
	C	16.5	109.3	16.7	111.8	1.14	3.5	1.6	30	5.9
Malmo	B	18.2	105.2			3.42	3.1	1.4		
	C	20.6	100.4			2.4	3.3	1.6		

1) material obtained in second sampling
SP = Swelling Potential (at omc)
PR = Penetration Resistance
q_u = unconfined compressive strength
I_q = unconfined compressive strength Index

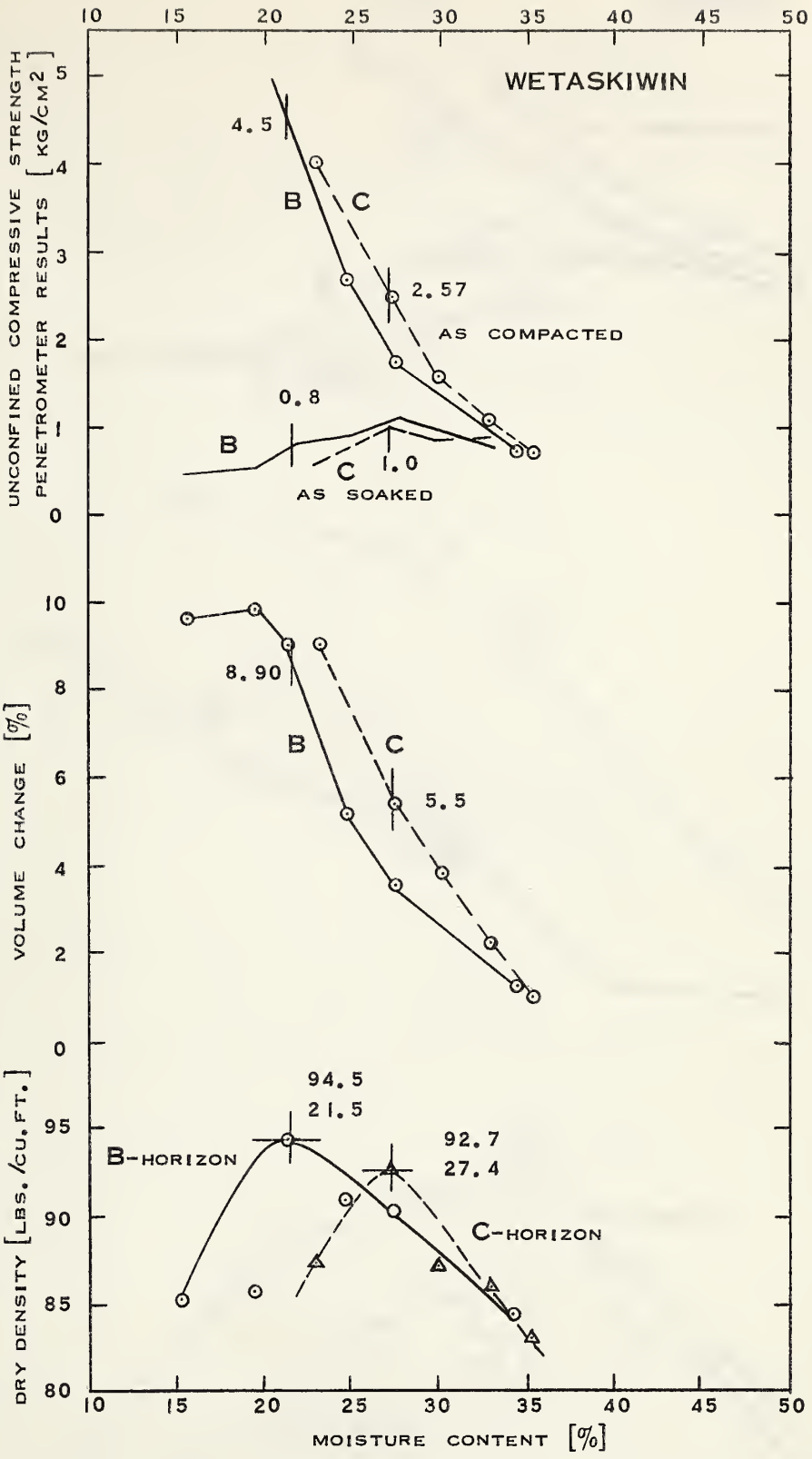


FIGURE 6A . – WETASKIWIN SOIL , SWELLING, PENETRATION AND COMPACTION TEST RESULTS .

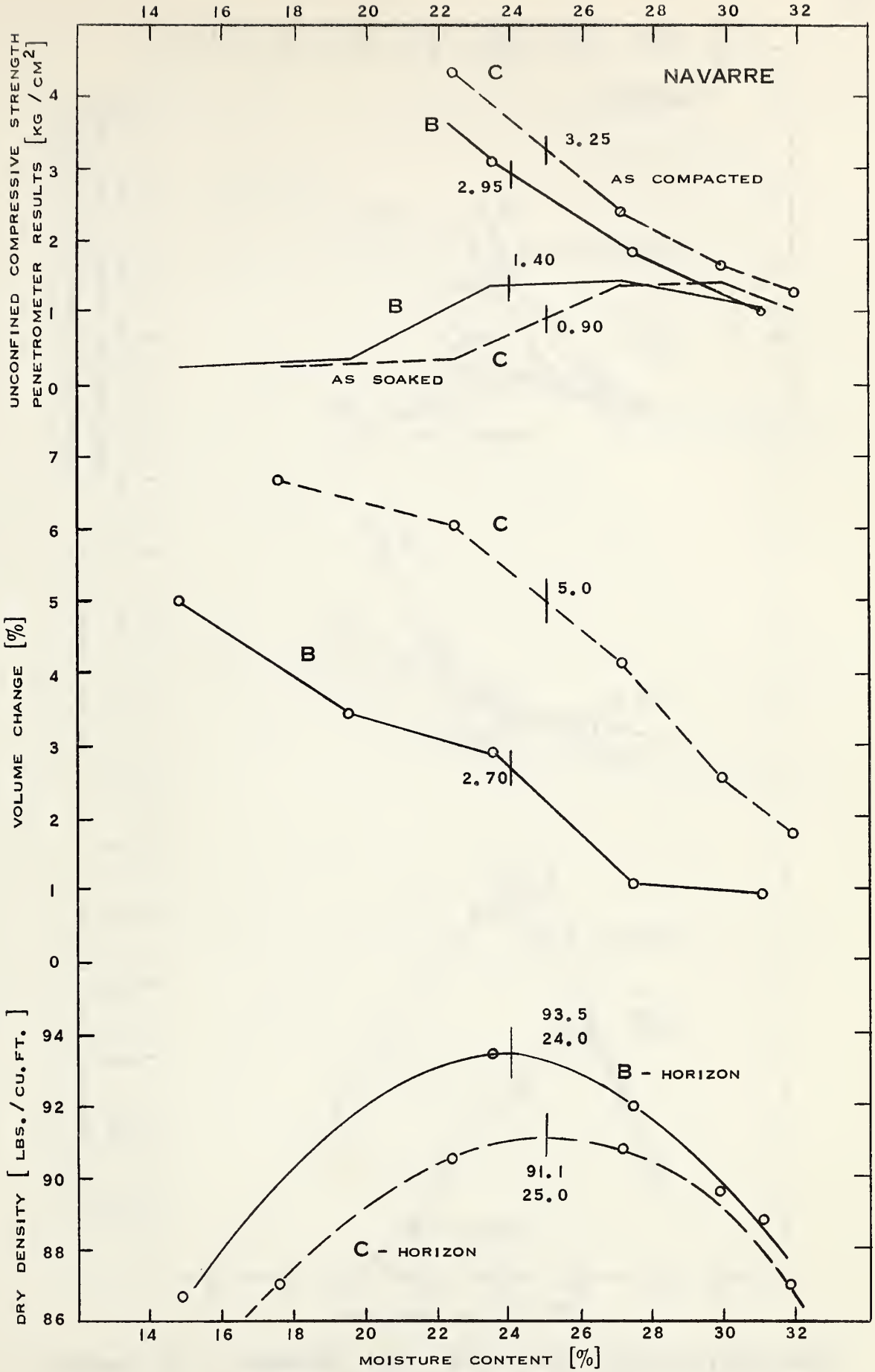
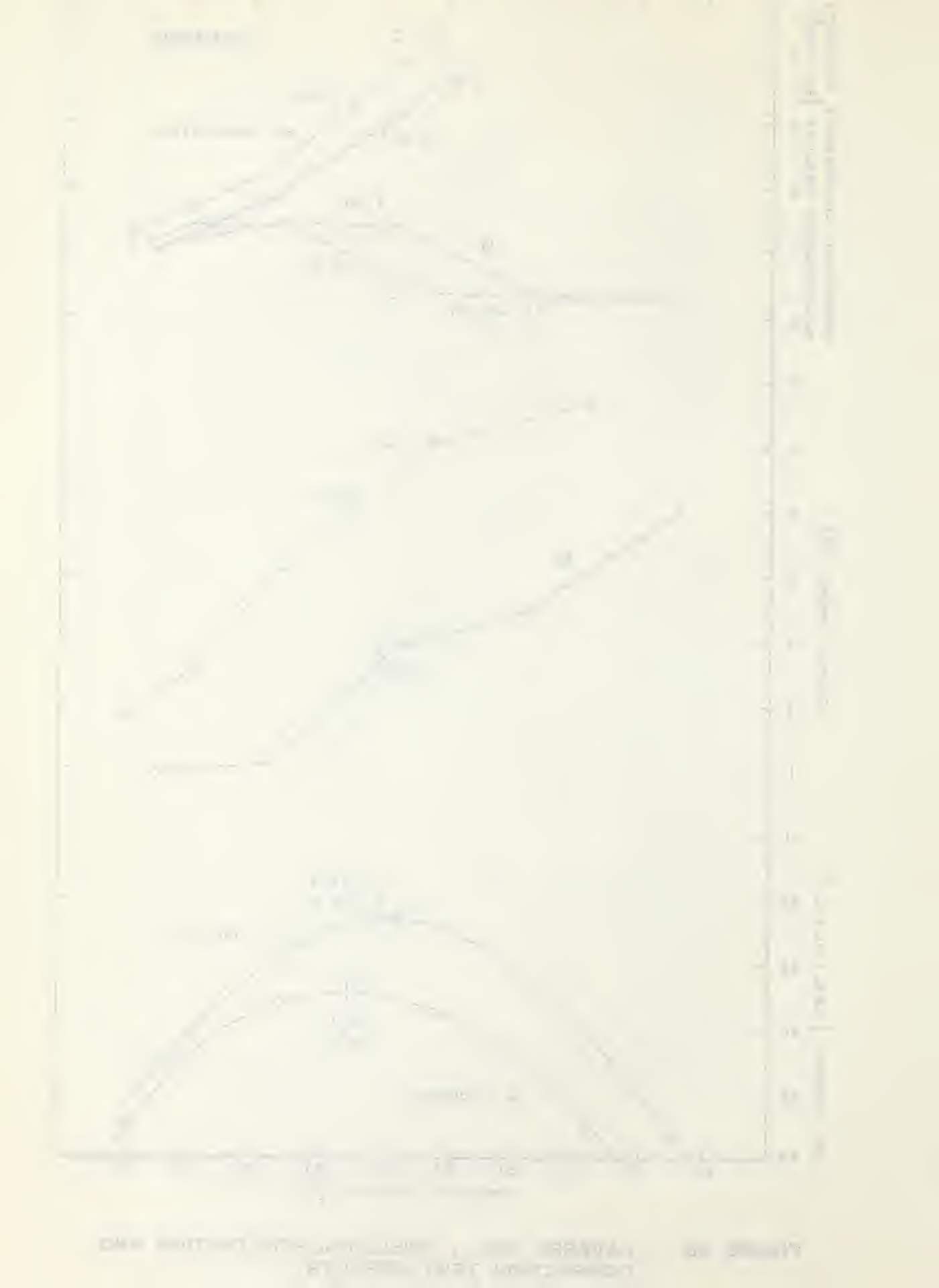


FIGURE 6B . – NAVARRE SOIL , SWELLING, PENETRATION AND COMPACTION TEST RESULTS .



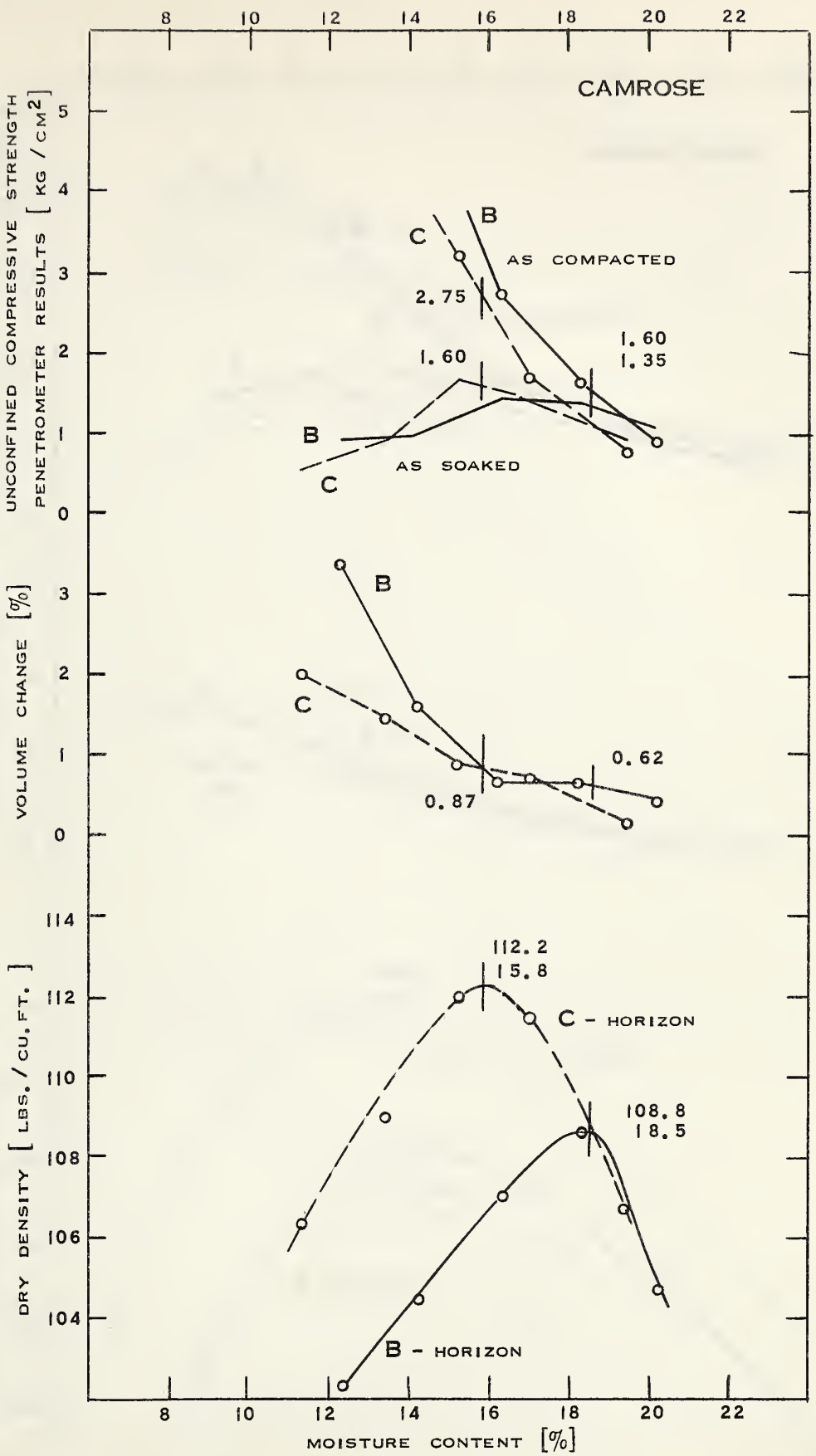


FIGURE 6C . – CAMROSE SOIL , SWELLING, PENETRATION AND COMPACTION TEST RESULTS .

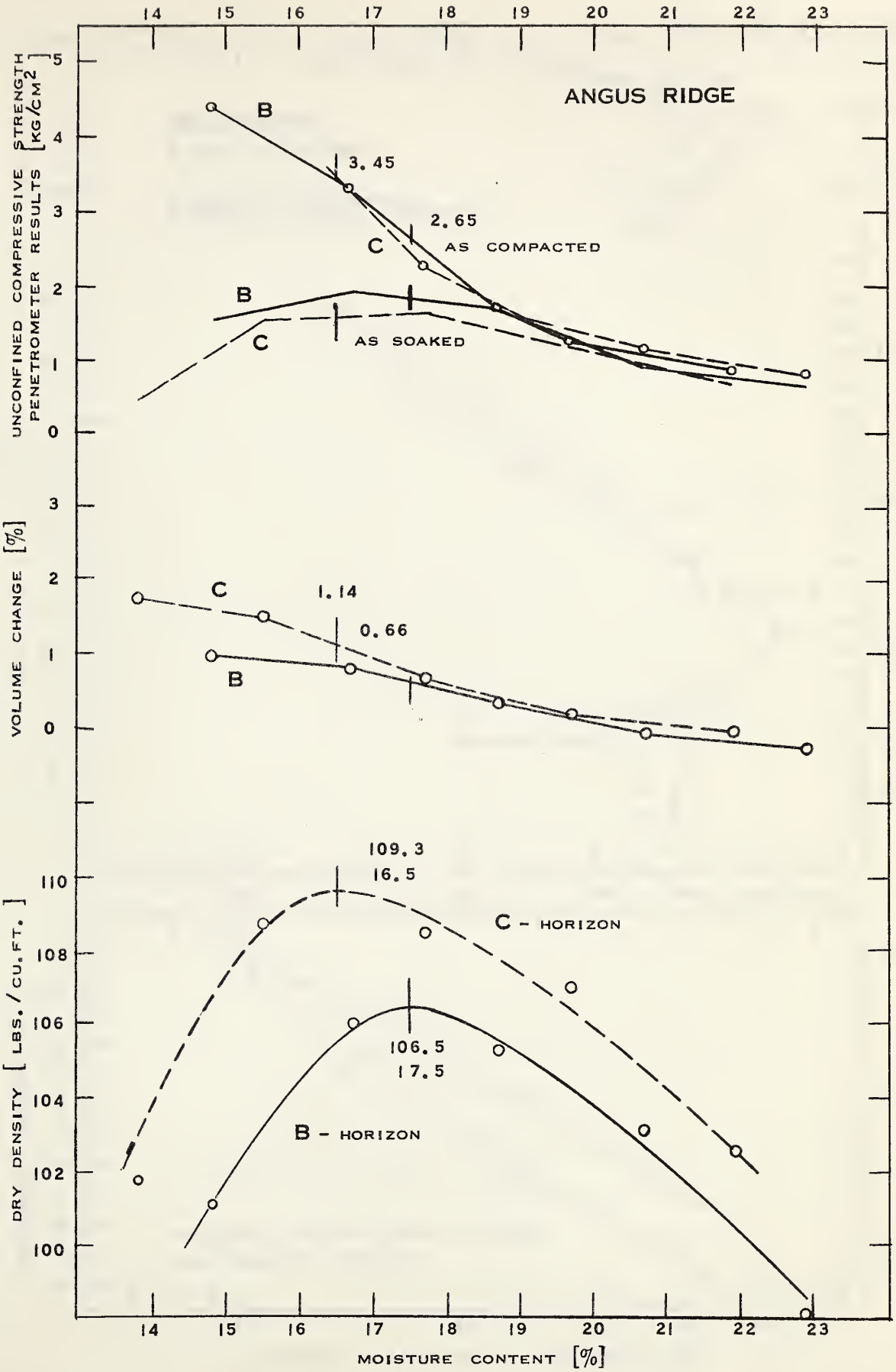


FIGURE 6D . – ANGUS RIDGE SOIL , SWELLING, PENETRATION AND COMPACTION TEST RESULTS .

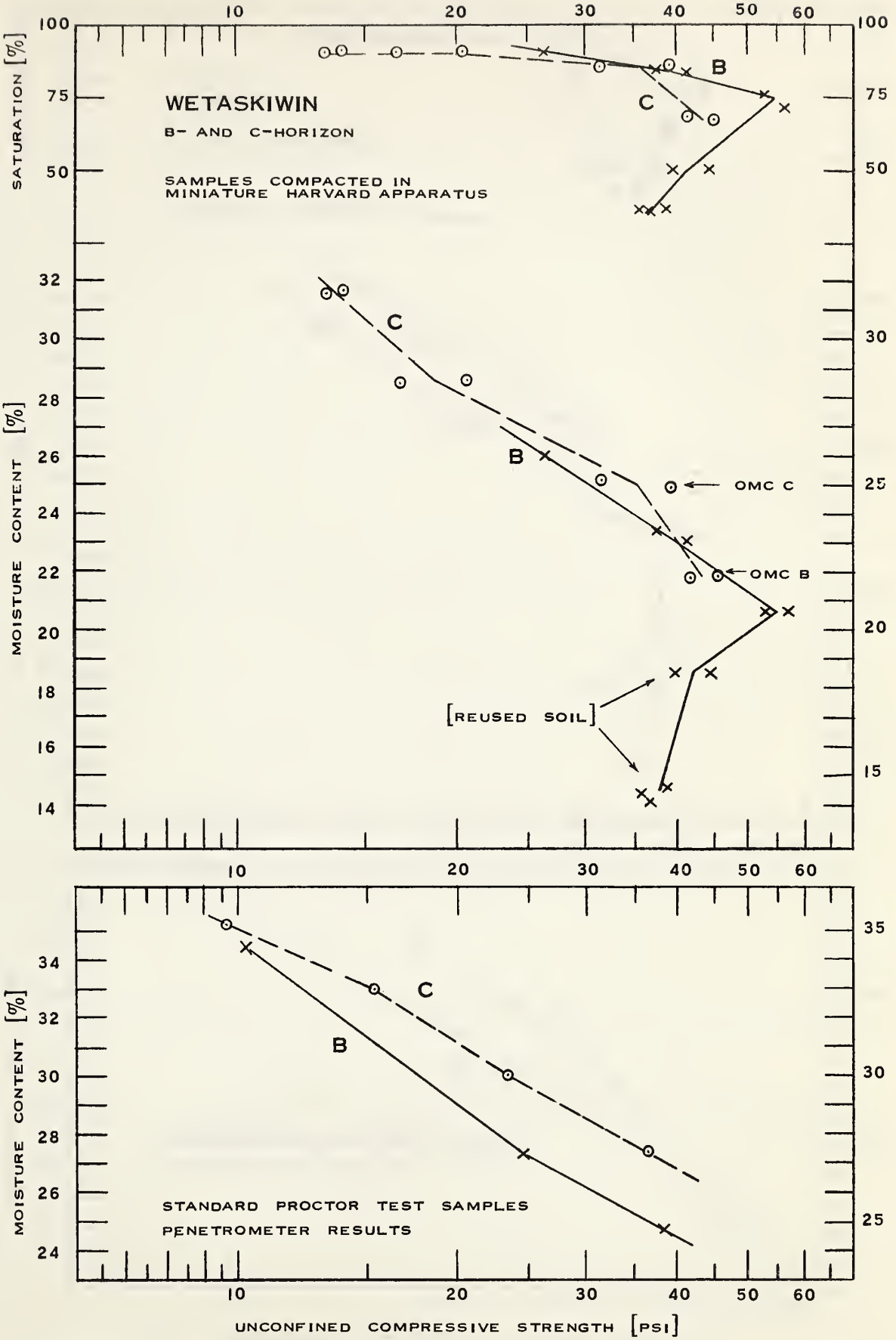


FIGURE 7. – UNCONFINED COMPRESSIVE STRENGTH VS. MOISTURE CONTENT, WETASKIWIN SOIL.

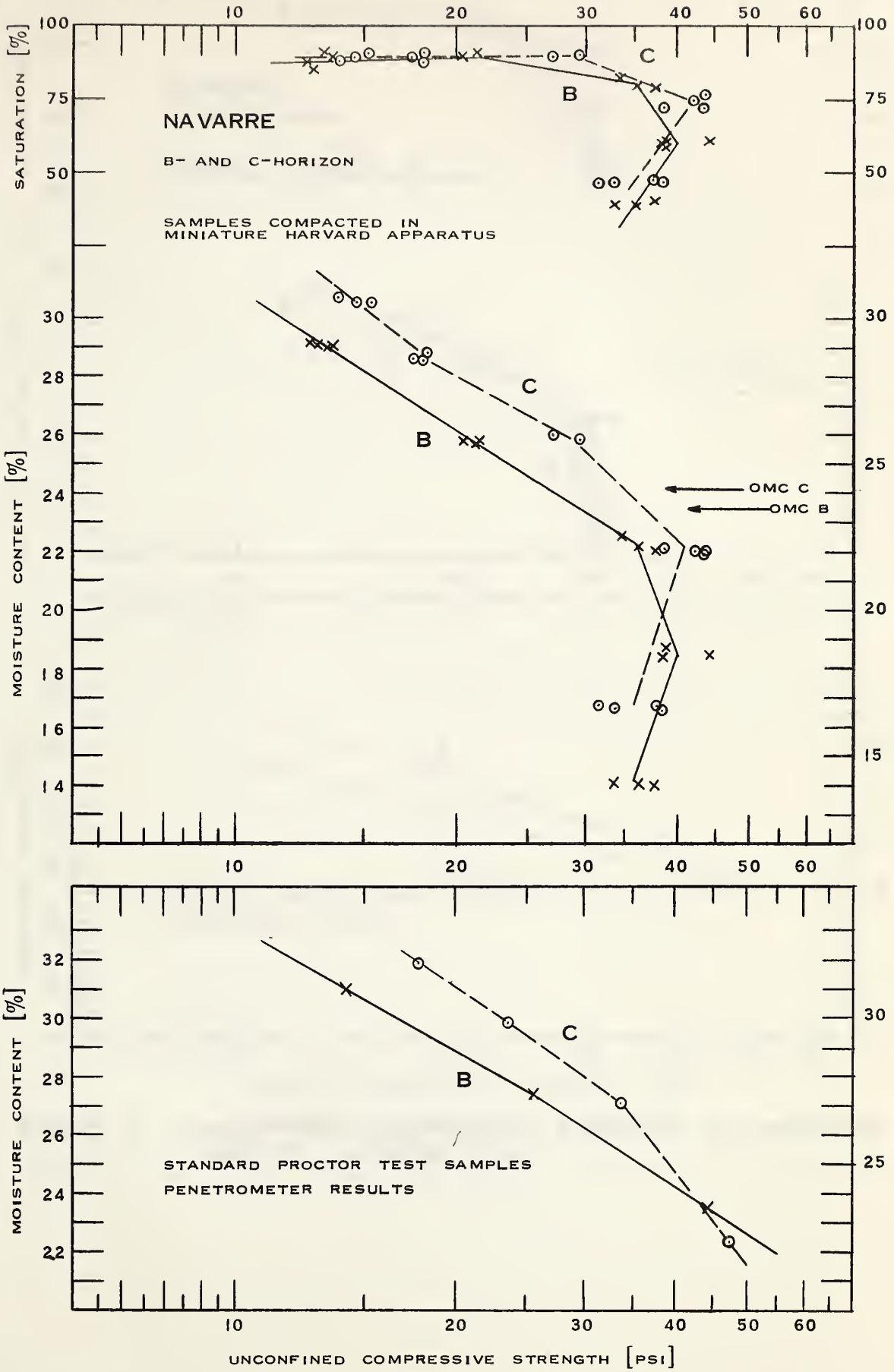


FIGURE 8. – UNCONFINED COMPRESSIVE STRENGTH VS. MOISTURE CONTENT, NAVARRE SOIL.

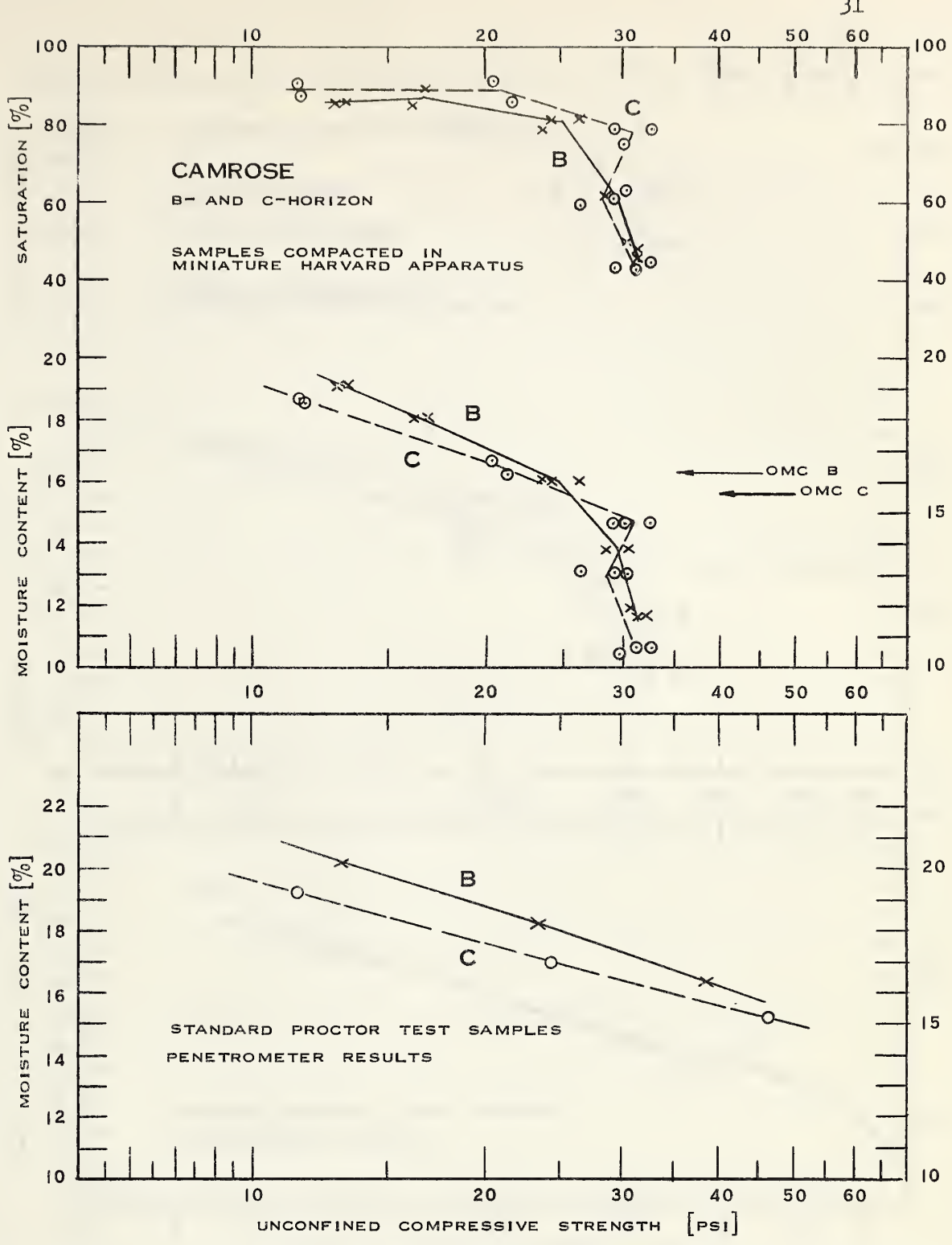


FIGURE 9. – UNCONFINED COMPRESSIVE STRENGTH VS. MOISTURE CONTENT, CAMROSE SOIL.

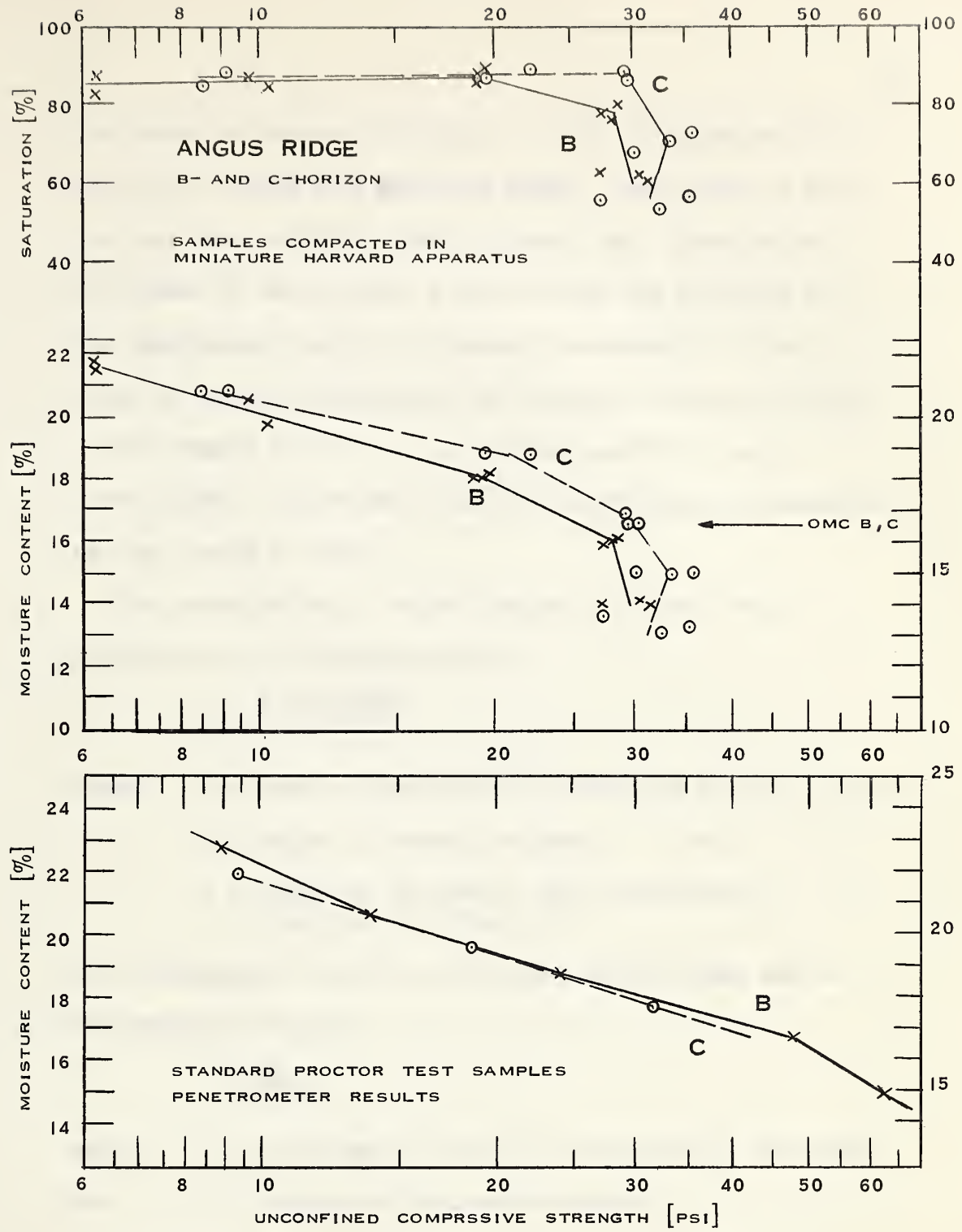


FIGURE 10. – UNCONFINED COMPRESSIVE STRENGTH VS. MOISTURE CONTENT, ANGUS RIDGE.

the amount of water-soluble salts in soil (Designation E-8). The soil is mixed with distilled water; the mixture is kept for four days, agitated several times a day. Then the soil is allowed to settle until a clear liquid can be poured off. The supernatant liquid is filtered if necessary. It was found in the tests performed, that despite filtering through a fine ceramic filter it is not always possible to get a clear liquid. The weight of soluble constituents is determined by oven drying at 110°C.

The concentration of soluble material in the liquid is computed by the following equation:

$$C = \frac{W \times 100\ 000}{V}$$

where: C = soluble constituents in parts per million (p.p.m.),

W = weight of residue in grams, and

V = volume to filtrate in cubic centimeters evaporated to obtain W.

The percentage of soluble constituents by dry weight may be determined as follows:

$$P = \frac{CD}{10\ 000}$$

where P = percentage of soluble constituents by dry weight

and D = dilution of soil-water mixture

For practical use, parts per million are considered to be equivalent to milligrams per liter.

The results of the soluble salt tests are included in TABLE VI. For each test 50 grams of soil were mixed with 1000 cm^3 of

TABLE V

CONSOLIDATION TEST DATA

FOR REMOULDED SOILS

SOIL TYPE	C_c load increm. 1-10 kg/cm^2	C_V at e = .8 (cm^2/sec) x 10^{-5}	K at e = .8 (cm/sec) x 10^{-10}	t_{100} at 7.82 kg/cm^2 (min)	EC pan water microhmos cm
Wkn. B	.48	2.3	5.7	140	1000
Wkn. C	.48	3.8	6.3	115	1800
Nv. B	.39	8.1	19	165	170
Nv. C	.44	4.0	7.0	215	230
Cam. B	.28	211	3100	19	1900
Cam. C	.38	117	1000	21.5	2300

Note: t_{100} values are for varying void ratios.

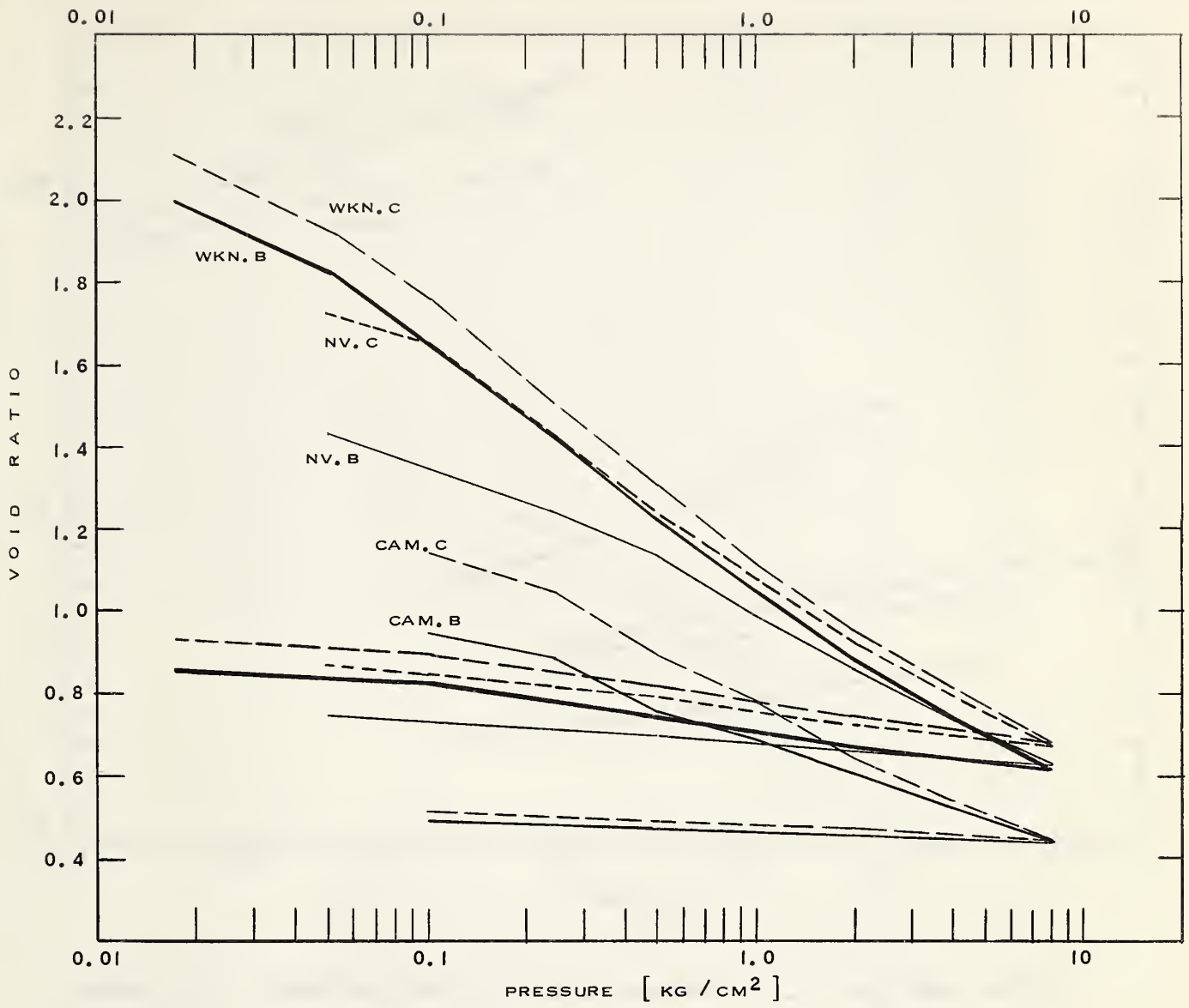


FIGURE II. – CONSOLIDATION PRESSURE VS. VOID RATIO.

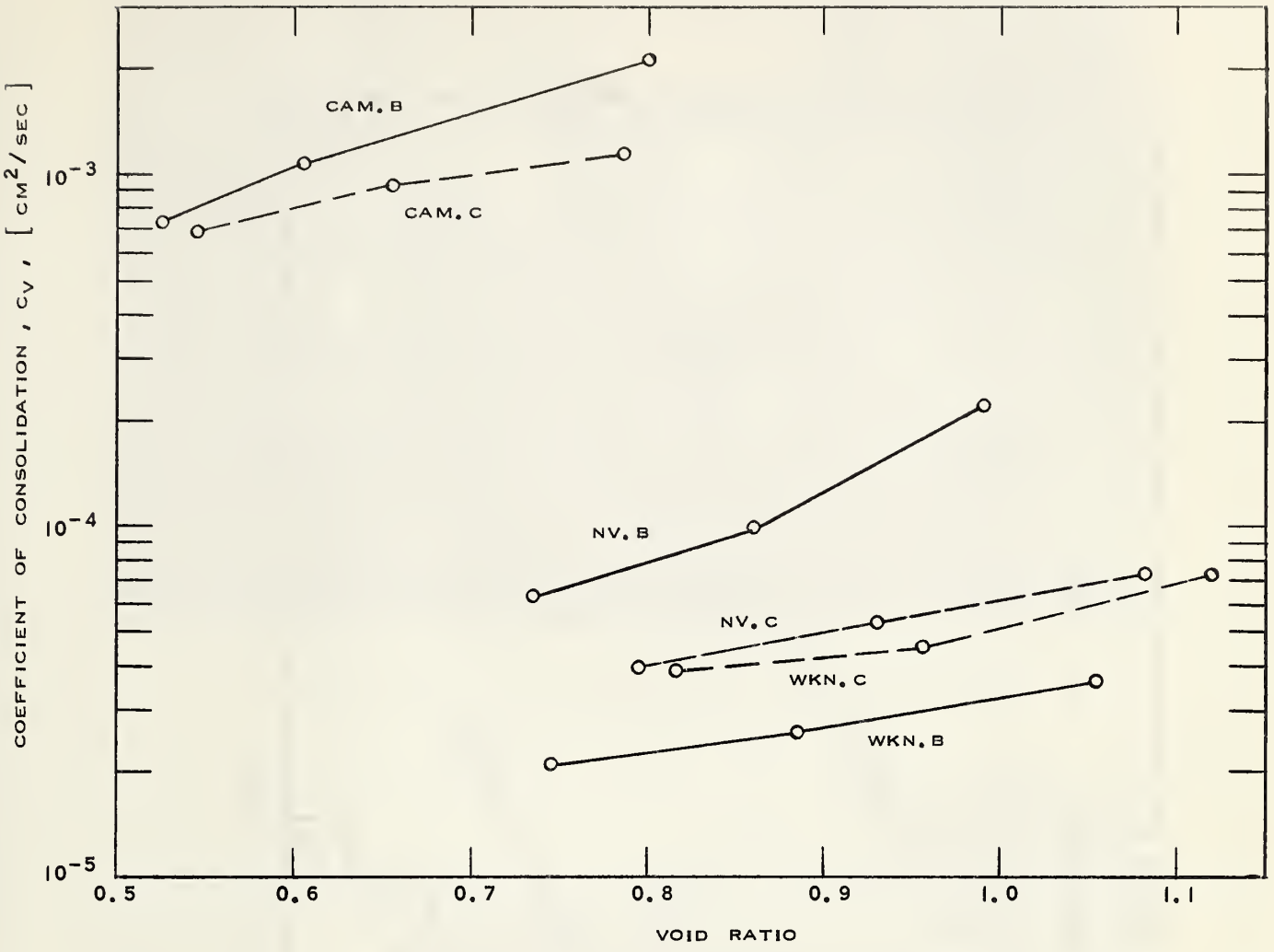


FIGURE 12. – COEFFICIENT OF CONSOLIDATION , C_v , VS. VOID RATIO.

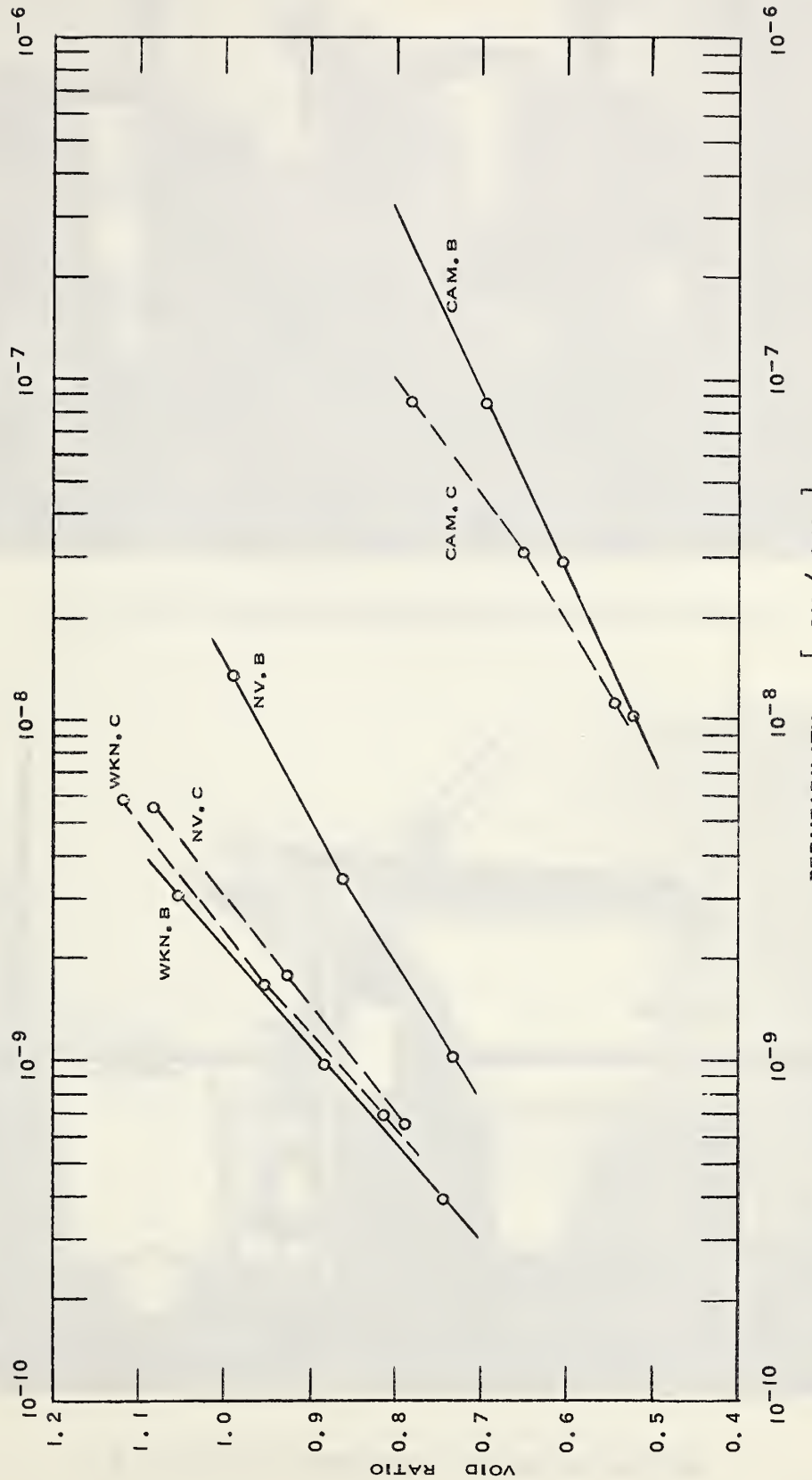
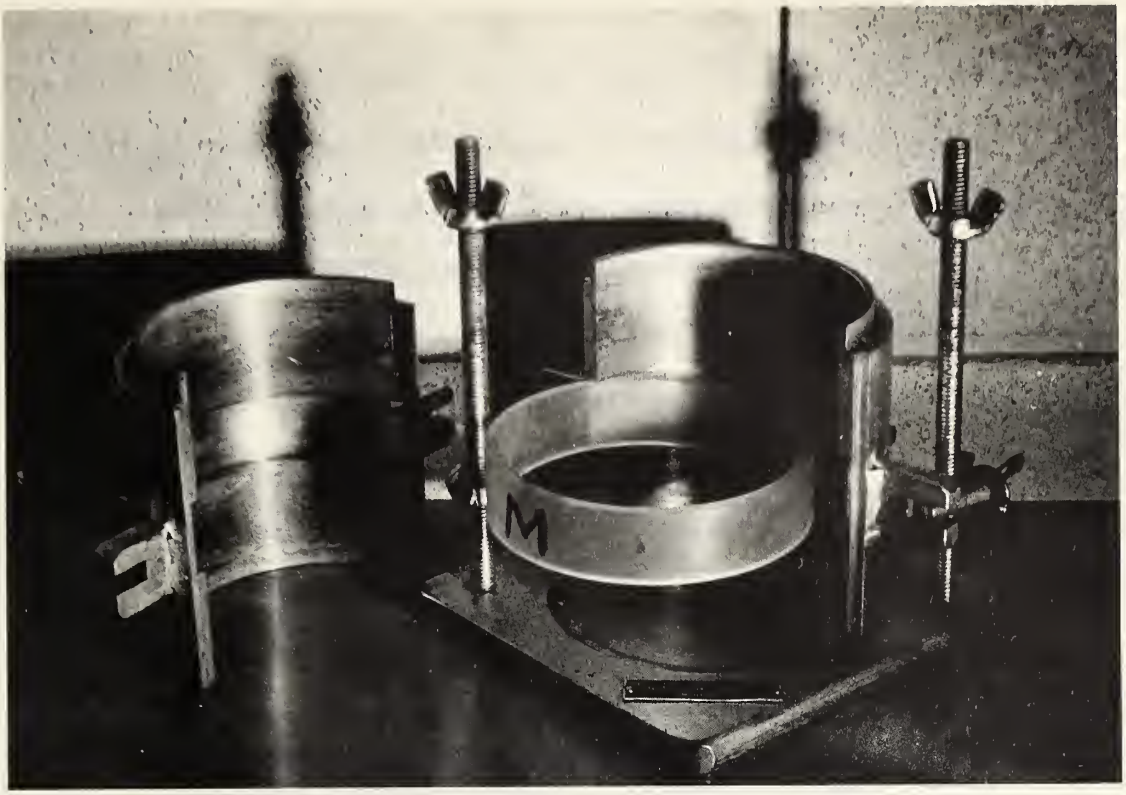
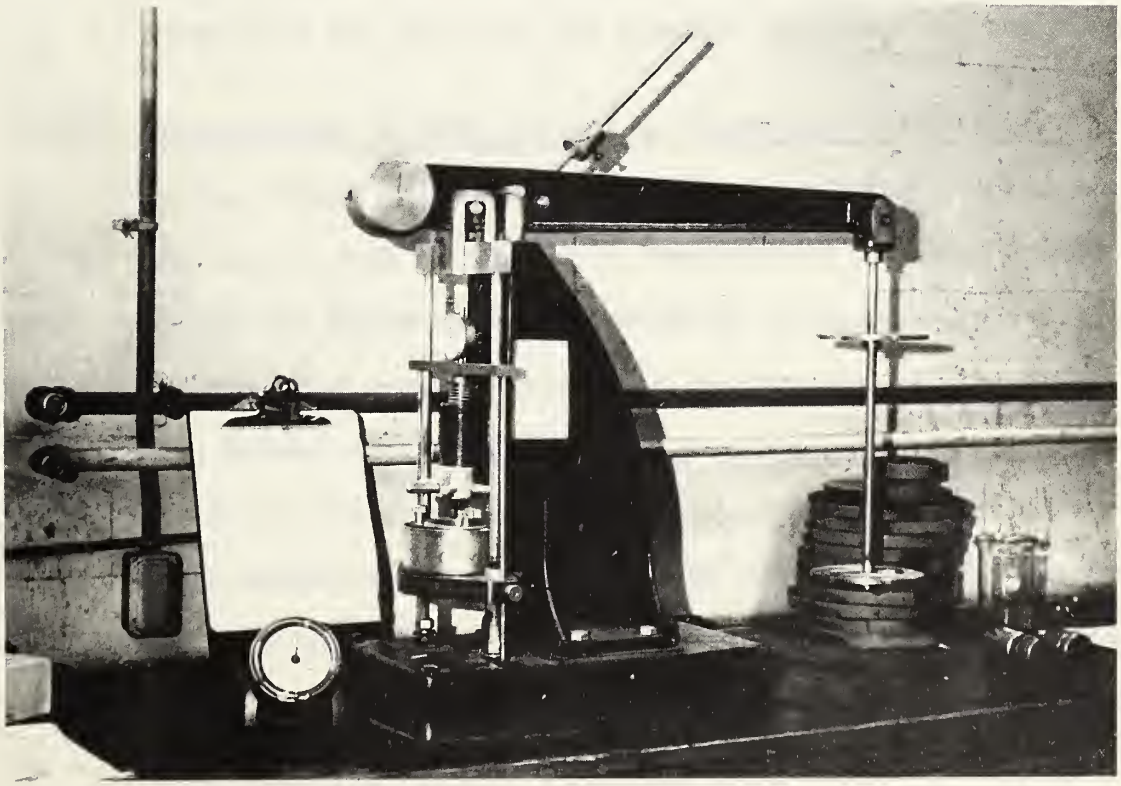


FIGURE 13.- PERMEABILITY VS. VOID RATIO [AS CALCULATED FROM CONSOLIDATION TEST RESULTS].



[A] SPLIT COMPACTION MOLD WITH LUCITE RING



[B] WYKHAM FARRANCE CONSOLIDOMETER

PLATE I

distilled water (D = 20). The results of Series 1 were obtained using the procedure as outlined above. In Series 2, 10 cm^3 of 3% HCl were added to 200 cm^3 of filtered liquid in order to precipitate colloidal matter, which caused some liquids to be turbid. A blank was run and showed that HCl is decomposed during the drying process in the oven and hence does not affect weight determinations directly.

The filter residues from the soluble salt determination were dried and weighed to 1/1000 of a gram. They were allowed to cool in a desiccator for 10 minutes before weighing. Absorption of moisture causes a rapid increase in weight and constitutes a serious problem in accurate weighing. This is illustrated by the data of TABLE VII which gives the weights of the residue, oven-dried and after one day exposure to normal air humidity.

(ii) Determination of salt content by electrical conductivity

The liquid used to determine soluble salts by evaporation was also tested for electrical conductivity. A Solu Bridge (PLATE 2A) manufactured by Industrial Instruments gave conductivity values expressed in micromhos/cm. Test results are listed in TABLE VI.

In FIG. 14 electrical conductivity values are plotted versus salt concentration as determined by the soluble salt test by weight. Also given in FIG. 14 are some relationships between EC and salt concentration for some pure salts, as published by the U.S. Dept. of Agriculture (1954).

4:2:2 Organic Matter

An attempt was made to evaluate the organic content using the H_2O_2-method as described by Ackroyd (1957). About 20 grams of soil are heated in a hydrogen peroxide solution at 60°C. The loss of oven-dried weight after the soil has been treated with H_2O_2 gives the percentage of organic matter.

This method was unsuccessfully used in 17 tests. Instead of decreasing, the weight of the sample increased due to the H_2O_2 treatment. This is considered further in subsequent discussions.

4:3 Summary of Engineering Tests

TABLE III summarizes engineering classification tests, including Atterberg limits, specific gravity and grain size analysis These properties give a good characterization of a soil used for engineering purposes. Numerous other soil properties have been related to liquid limit, plasticity index, percent clay, etc.

TABLE IV reports on compaction, swelling and strength tests. Moisture-density relationships were determined by two methods: Standard Proctor and Miniature Harvard compaction tests. Swelling Potential and penetration resistance were measured on soil compacted in the proctor mold. The unconfined compressive strength was obtained of samples formed in the Miniature Harvard device.

TABLE V informs about properties determined from conventional consolidation tests, such as compressive index and permeability.

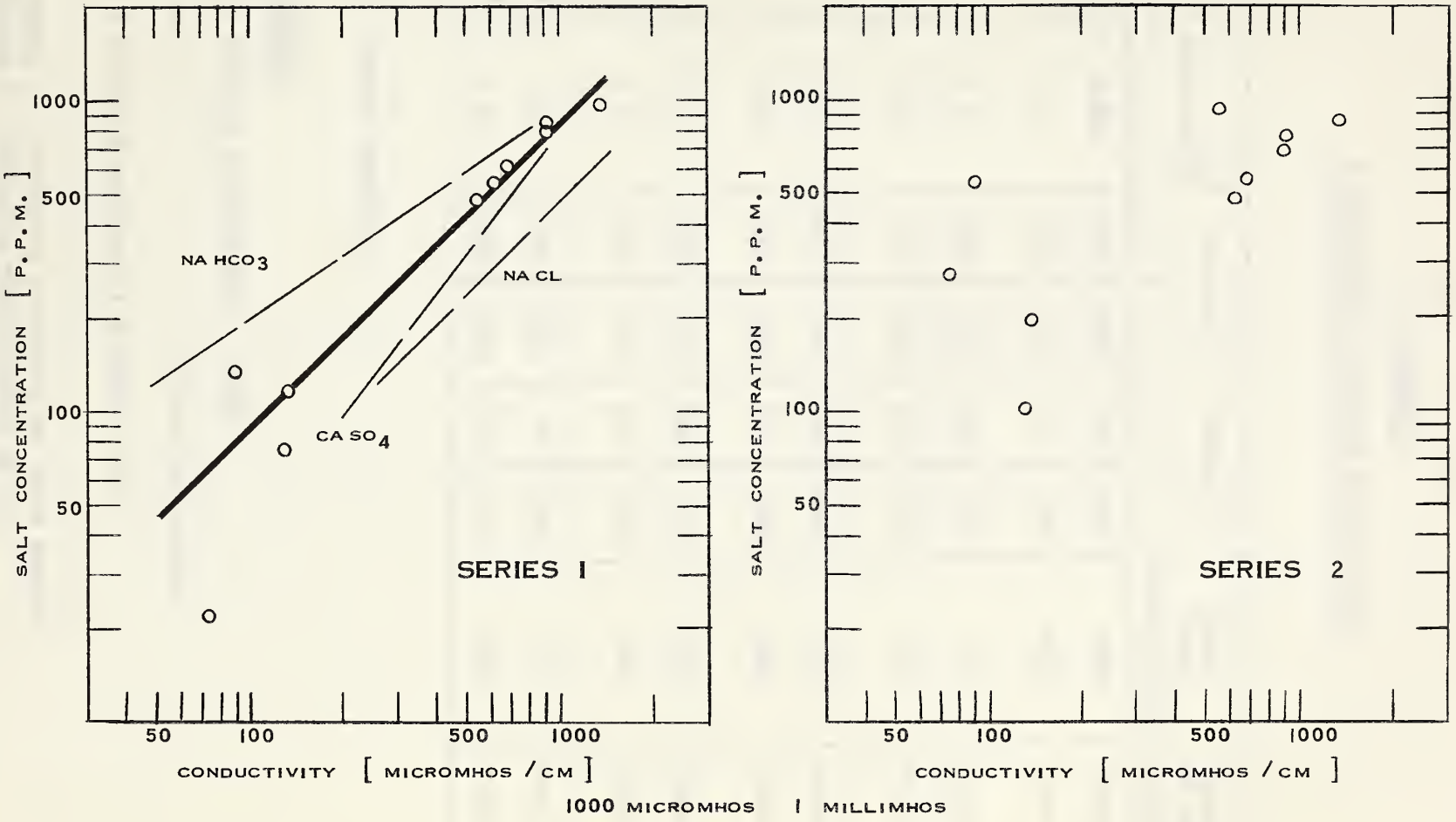


FIGURE 14. – ELECTRICAL CONDUCTIVITY VS. SALT CONCENTRATION.

TABLE VI

SOLUBLE SALT TEST AND CONDUCTIVITY

SOIL TYPE	$W_{air\ dry}$(%)	Series 1		Series 2		Elect. Cond. micromhos/cm	Appearance of Soil Suspension
		C	P	C	P		
Wkn. B	4.44	428	0.86	485	0.97	550	turbid
Wkn. C	3.1	856	1.71	976	1.95	1035	flocc.
Nv. B	3.4	540	1.08	136	0.27	90	very turb.
Nv. C	4.5	193	0.38	115-	0.23	135	very turb.
Cam. B	3.8	484	0.97	539	1.08	615	turbid
Cam. C	2.4	733	1.47	812	1.62	900	flocc.
Ar. B	2.7	550	1.10	614	1.23	670	flocc.
Ar. C	2.7	756	1.51	829	1.66	900	flocc.
Nv. B[1)]	5.4	279	0.56	22	0.04	75	very turb.
Nv. C[1)]	3.2	100	0.20	74	0.15	130	turbid

1) Second sampling

REMARKS:

C = soluble constituents (ppm)

P = " " (% air dry weight)

D = Dilution water-soil mixture = 20:1

Series 1: Procedure according to Earth Manual
Series 2: Colloids precipitated by Hcl

TABLE VII

WEIGHT OF RESIDUE

	Type of Soil		Weight oven dry (gm)	Weight air dry (gm)	Gain in weight %
Series 1	Wkn.	B	0.0855	.1024	20
		C	0.1712	.1835	7
	Nv.	B	0.1080	.1222	13
		C	0.0383	.0455	19
	Cam.	B	0.0968	.1102	14
		C	0.1466	.1572	7
	Ar.	B	0.1100	.1200	9
		C	0.1511	.1625	7
	Nv.[1]	B	0.0557	.0632	14
		C	0.0199	.0270	36
Series 2	Wkn.	B	0.0737	.0812	10
		C	.1873	.1929	3
	Nv.	B	.0210	.0287	37
		C	.0149	.0250	68
	Cam.	B	.0911	.0994	9
		C	.1607	.1705	6
	Ar.	B	.1110	.1235	11
		C	.1524	.1629	6
	Nv.[1]	B	.0030	.0183	510
		C	.0102	.0225	121
	Blank		-.0024	+.0025	

1) Second sampling

CHAPTER V

SOIL SCIENCE PROCEDURES AND RESULTS

5:1 Standard Tests

5:1:1 Mechanical Analysis (Pipette Method)

The pipette method of mechanical analysis is the standard method used by the Alberta Soil Survey. Ten gm. of air-dried soil is used in one test. The moisture content of the air-dried soil is determined on a separate sample. The pre-treatment consists first of adding 0.2N HCl gradually until the evolution of CO_2 ceases. The soil suspension is then made to 50 ml , 5 ml of 33% H_2O_2 is added and the beaker heated on a steam bath overnight. If the soil contains much organic matter, more H_2O_2 may be added. The sample is transferred to a 100 ml plastic centrifuge tube, a few drops of dilute HCl is added and the sample centrifuged. When the soil is sedimentated, the supernatant solution is poured off. The tube is filled up with distilled water, the soil is brought into suspension and again placed in the centrifuge. The sedimented soil sample is transferred to an electric mixer, distilled water added and mixed 10 to 15 minutes. The sample is now filtered through a No. 300 mesh sieve into a 1000 ml sedimentation cylinder. Weighing the residue on the sieve will give the percentage of sand. Ten ml of a dispersing agent is added, which contains 35.7 gm. of sodium hexametaphosphate (Calgon) and 7.9 gm. of Na_2CO_3 per liter. Before

starting the sedimentation test, the soil suspension is stirred with a plunger for five minutes. Twenty-five ml of soil suspension removed after a certain elapsed time and at a certain depth by means of the pipette will indicate the percentage of clay contained in the sample. The temperature of the suspension is kept constant at 25°C. Part of the pipette sample is further centrifuged for 33 min. at 1200 r.p.m. Then 5 ml of soil suspension is removed from a depth of 2 cm in the centrifuge tube for the determination of the amount of fine clay. Thereby the percentage of sand, clay and fine clay is determined directly. The difference to a 100% represents the percentage of silt. Thereby four points of the grain size distribution curve are obtained.

Test results are given in TABLE VIII. According to the Soil Texture Triangle (FIG. 15) Wetaskiwin and Navarre soils would be classified as heavy clays, Camrose as clay loam and the Angus Ridge series as sandy clay loam.

5:1:2 Total Exchange Capacity and Exchangeable Cations

The standard procedure of the Alberta Soil Survey was used, in order to determine the amount of exchangeable cations. Ten grams of soil is used for one test. The soil is first leached with 1 N NH_4Ac. Part of the leachate is saved for Ca, Mg, Na, and K determination on the Beckman flame photometer (see PLATE 2c). The soil is subsequently leached with 95% ethyl alcohol, which removes all free NH_4Ac. The soil is then leached with several successive portions of 1N NaCl. The NaCl leachate is made to a final volume of 250 ml using distilled water. The ammonia content of this leachate is determined by distilling by the

TABLE VIII

SOIL SCIENCE MECHANICAL ANALYSIS

SOIL TYPE		PER CENT					
		Sand 0.05	Silt 0.05 0.002	Clay 0.002	Fine Clay	Total Clay	1)
Wkn.	B	18.2	9.0	48.5	24.3	72.8	
	C	14.8	8.8	53.8	22.6	76.4	
Nv.	B	13.6	1.4	56.6	28.4	85.0	
	C	11.2	5.2	55.0	28.6	83.6	
Cam.	B	43.2	22.1	21.4	13.3	34.7	
	C	43.9	26.0	19.4	10.	30.1	
Ar.	B	46.0	22.0	20.6	11.4	32.0	
	C	46.5	25.0	18.1	10.4	28.5	

1) Engineering Classification

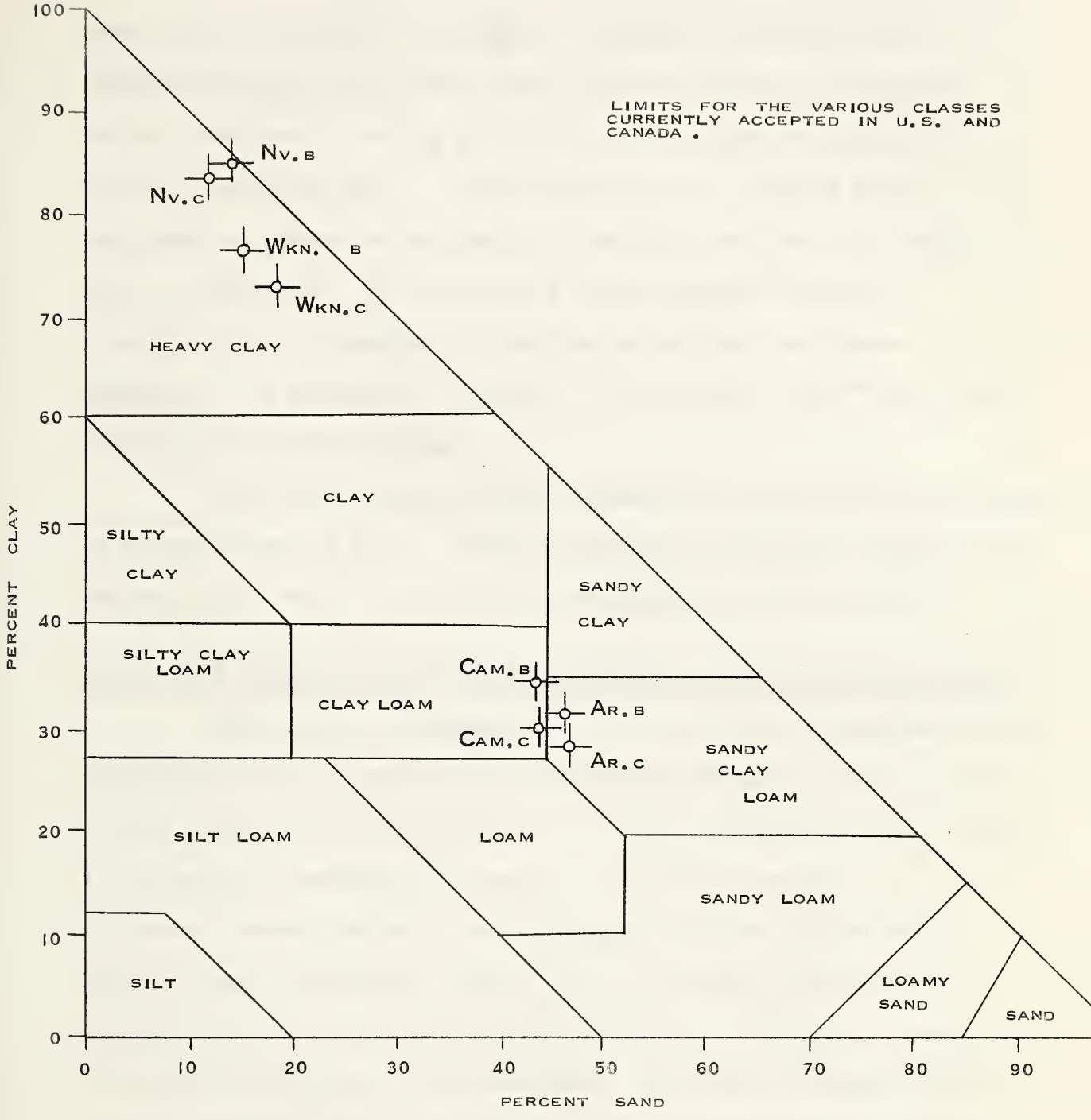


FIGURE 15. – SOIL TEXTURE TRIANGLE

magnesium oxide method (AOAC 1955). Ammonia is recovered in 4 per cent boric acid solution. Ammonia is determined by titrating with standardized H_2SO_4 using brome creasol green and methyl red indicator. The unit employed in dealing with exchange capacities and reactions is the milliequivalent (me). One milliequivalent is defined as one milligram of hydrogen or the amount of any other ion that will combine with or displace it. If a clay has a cation-exchange capacity of 1 me/100 grams it is capable of adsorbing and holding 1 milligram of hydrogen or its equivalent (e.g. 40/2 = 20 milligrams of Ca^{++}) for every 100 grams of air-dry substance.

TABLE IXa summarizes cation exchange data expressed in me/100 grams of air-dried soil (a.d.s.). TABLE IXb indicates the amount of the various cations in per cent of the sum of the exchangeable Ca, Mg, Na and K.

5:1:3 Salt Content as Estimated from Analysis of Cation Exchange Complex

The amount of exchangeable Na, K, Ca and Mg as determined by the procedure outlined previously includes adsorbed cations as well as free cations contained in the pore water. The total exchange capacity, however, is determined by measuring the amount of fully adsorbed NH_4 only. The difference between the sum of the exchangeable cations (approximately equal to sum of predominant cations Na, K, Ca and Mg) and the total exchange capacity, expressed in milliequivalents, is therefore a measure of the free electrolyte in the pore water. This value has been used to evaluate the salt content in homionic soils as investigated in previous research at the University of Alberta (e.g. Locker 1963). Values of salt content as calculated by this method are also given in TABLE IXa, designated

as "ΣCat.-TEC".

5:1:4 Electrical Conductivity of Saturation Extract

The conductivity of the saturation extract is recommended as a general method for appraising soil salinity in relation to plant growth (U.S. Dept. of Agriculture, 1954). A saturated soil paste (slightly in excess of w_L) is allowed to stand several hours. By means of vacuum extraction or centrifuging, a solution of the soluble constituents of the soil is obtained. The electrical conductivity of the extract is measured by a direct indicating bridge. Electrical conductivity (EC) is usually expressed in millimhos per cm. (Electrical conductance is expressed in mhos, reciprocal ohms). Test results may be found in TABLE IXa.

5:1:5 Property Changes with Depth in a Soil Profile

Samples were taken each five inches along the upper part of the profiles of the Wetaskiwin, Navarre, Camrose and Angus Ridge series. Three properties were determined: the natural moisture content, the amount of soluble salt by weight and the electrical conductivity of a saturation extract. The salt content was measured using the method outlined in the Earth Manual. The liquid obtained from the sedimentated soil suspension was filtered through Whatman No. 40 paper; however in some cases, brownish colloidal matter could not be removed by this method.

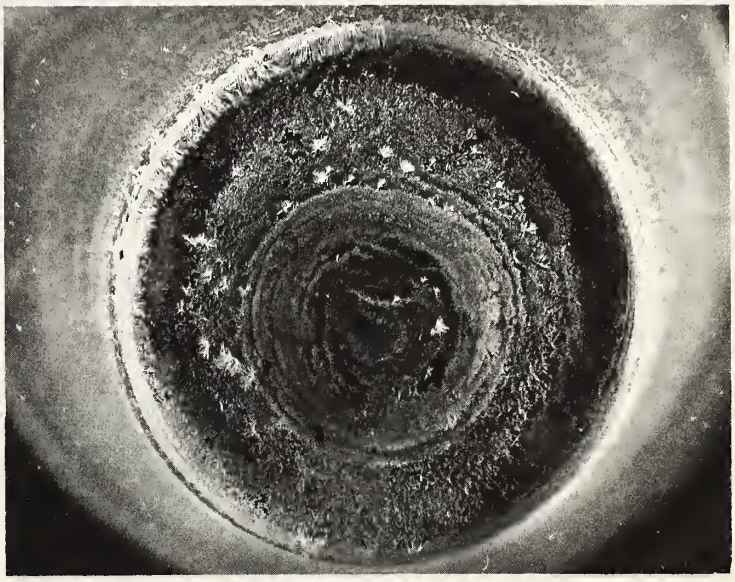
Test results are presented in FIG. 16.

5:1:6 Total Carbon

Total carbon (organic and inorganic) was determined by dry

[A] SOLU CONDUCTIVITY BRIDGE

[B] CRYSTALLIZED SALT EXTRACTED FROM SOIL



[C] BECKMANN FLAME PHOTOMETER

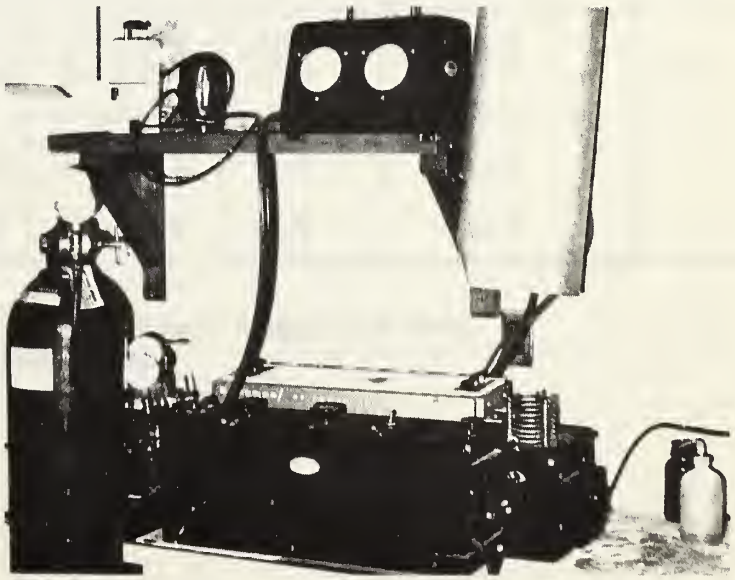


PLATE 2

TABLE IXa

SOIL SCIENCE ANALYSIS, TEST RESULTS

SOIL TYPE		TEC (me/100g)	Exch. Cations (me/100g a.d.s.) Ca	Mg	Na	K	Cat. - TEC (me/100g)	EC Saturation Ext. (millimhos/cm)	REMARKS
Wkn.	B	33.5	17.2	12.1	11.8	0.5	8.1	8.9	fresh
		42.6	18.4	15.0	11.7	0.8	3.3	7.5	reused 1)
		38	19	13	7	0.9	2	8.5	local 2)
		31.4	24.3	17.0	10.6	0.9	21.3	8.4	3)
	C	50.8	31.0	14.9	13.3	0.5	8.9	10.0	fresh
		32.3	35.4	15.5	13.6	1.0	33.2	11.0	1)
		52	41	12	8	0.9	9.9	12.7	2)
		34.0	42.5	17.4	6.8	0.9	34.5	9.6	3)
Nv.	B	42	23	14	3	0.9	-1.1	0.7	
		32.8	21.6	10.6	0.8	0.9	1.2	0.9	3)
	C	45	43	12	4	0.9	14.9	1.5	
		48.7	44.0	13.0	1.9	0.9	11.1	1.0	3)
Cam.	B	19.2	9.2	13.7	10.3	0.4	14.4	15+	
		17.3	8.6	15.5	6.6	1.3	14.6	14.1	3)
	C	16	24.0	9.8	7.7	0.3	25.8	14.0	
		13.6	30.0	20.8	9.6	0.8	57.5	15.0	3)
Ar.	B	20.3	23.0	14.0	5.6	0.6	22.9	9.5	
		17.7	5.0	10.9	6.6	0.9	5.7	10.6	3)
	C	15.8	25.0	16.1	7.8	0.4	33.5	12.1	
		17.7	45.3	13.9	7.5	0.7	49.6	7.7	3)
Malmo	B	24.0	15.5	4.0	0.1	0.3	-4.1	0.7	
	C	21.4	29.4	4.5	0.2	0.3	13.0	0.5	

1) Air dried and reused after Proctor compaction test
2) Local, sample from Shelby tube
3) Second sampling

TABLE IXb

SOIL SCIENCE ANALYSIS, TEST RESULTS

SOIL TYPE		Exch. Cations (%) Ca	Mg	Na	K	Remarks
Wkn.	B	41.3	29.0	28.5	1.2	fresh
		40.0	32.8	25.5	1.7	reused 1)
		47.6	32.6	17.5	2.3	local 2)
		46.0	32.2	20.1	1.7	3)
	C	51.9	25.0	22.3	0.8	
		54.0	23.6	20.9	1.5	1)
		66.2	19.4	12.9	1.5	2)
		62.9	25.7	10.1	1.3	3)
Nv.	B	56.3	34.2	7.3	2.2	
		63.7	30.4	2.3	2.6	3)
	C	71.8	20.0	6.7	1.5	
		73.5	21.7	3.2	1.5	3)
Cam.	B	27.4	40.8	30.6	1.2	
		26.9	48.6	20.5	4.0	3)
	C	57.5	23.4	18.4	0.7	
		56.2	29.2	13.5	1.1	3)
Ar.	B	53.2	32.4	13.0	1.4	
		21.4	46.2	28.1	3.7	3)
	C	50.7	32.7	15.8	0.8	
		67.1	20.6	11.1	9.7	3)
Malmo	B	77.9	20.1	0.5	1.5	
	C	85.4	13.1	0.6	0.9	

1) Air dried and reused after Proctor compaction test
2) Local, sample from Shelby tube
3) Second sampling

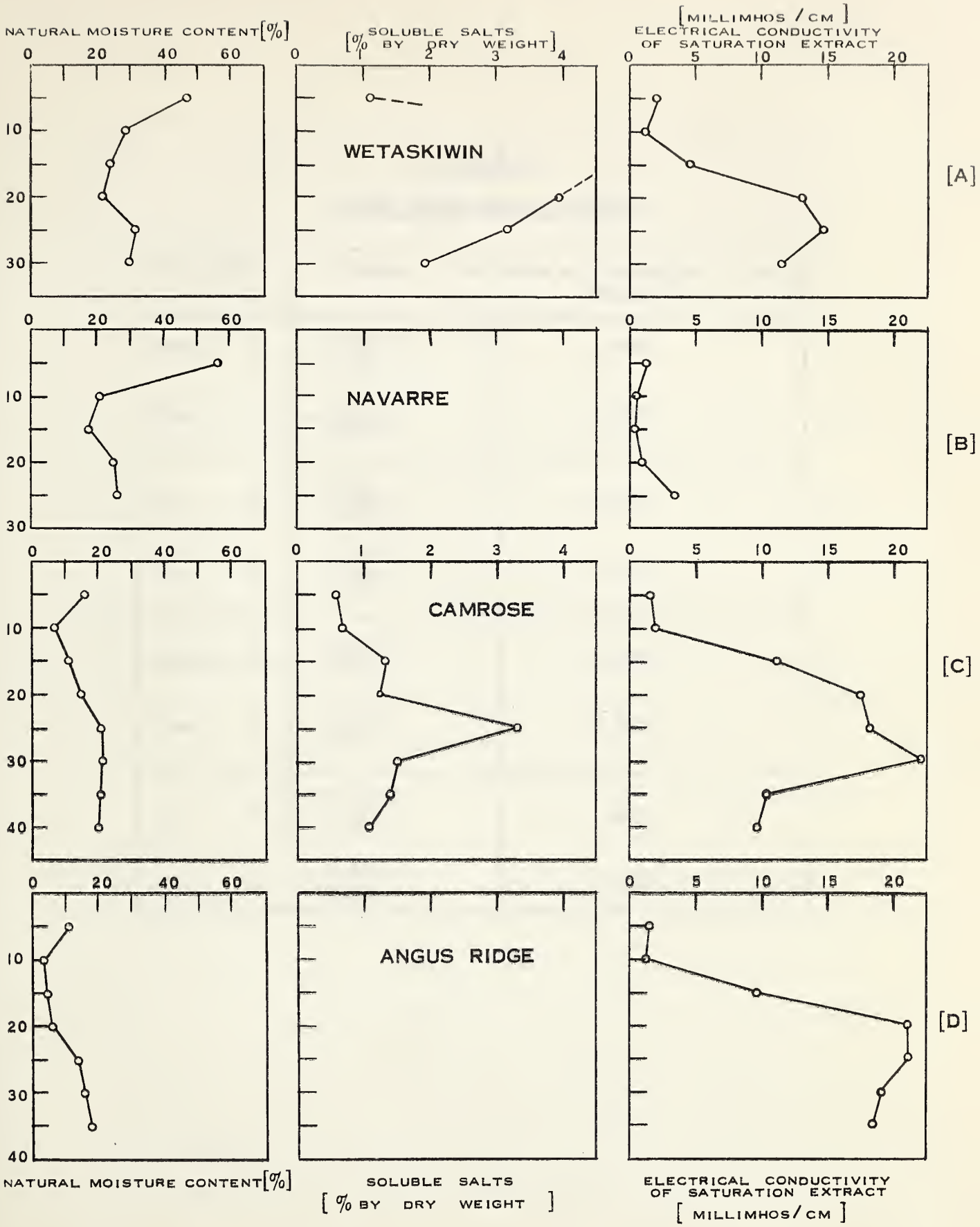


FIGURE 16 A-D . – VARIATION OF NATURAL MOISTURE CONTENT AND SALT CONTENT WITH DEPTH IN VARIOUS SOIL PROFILES .

TABLE X

TOTAL CARBON TEST: RESULTS

SOIL TYPE	% Carbon (on basis of dry weight of soil)	average
Wkn. B	0.831 0.787	0.809
Wkn. C	1.133 0.823	0.987
Nv. B	0.631 0.673	0.652
Nv. C	0.908 0.934	0.921
Cam. B	0.679 0.701	0.690
Cam. C	0.537 0.487	0.521
Ar. B	1.107 1.020	1.019
Ar. C	1.381 1.412	1.396

combustion in a tube at about 925°C. Alundum, MnO_2 and CuO are used as catalysts. A stream of air is passed through the tube. It carries the CO_2 through a purification train and into an absorption bulb containing ascarite. Weighing the bulb before and after combustion of the sample gives the weight of CO_2 evolved. The percentage carbon is determined as

$$\%C = \frac{\text{wt. } CO_2}{\text{wt. soil}} \times \frac{27.27}{1}$$

About 3 to 5 grams of air-dried soil were used for each test. Results are given in TABLE X. Two tests were run for each soil type. This test method is a standard procedure used by the Alberta Soil Survey (Reference: A.O.A.C. 1955).

5:2 Special Test

X-Ray analysis of clay minerals

The X-ray diffraction method was used to identify the predominant clay minerals and estimate their relative quantities.

A soil-water suspension was prepared in the same manner as for a grain size analysis and allowed to settle under controlled temperature conditions. After a certain elapsed time a sample containing only particles smaller than 0.002 mm equivalent diameter was removed by means of a pipette from a depth determined according to Stokes' Law. Another sample with a maximum particle size of 0.001 mm was obtained by the same basic procedure. A few drops of the suspension collected by the pipette were allowed to sediment onto a glass microscope slide and air dried. This sample preparation promotes an orientation of the clay particles parallel to the plate, thus

enhancing reflection of X-rays on basal planes and allowing easier interpretation of the test results. Diffraction data, using a recording spectrometer, were obtained for each sample without further treatment, following saturation with glycol, and after subsequent heating to 450°C for about 15 minutes. FIG. 17 shows the X-ray diffraction data for Wetaskiwin soil. All three diagrams are used for identification purposes. Montmorillonite swells in glycol to a characteristic layer spacing of about 17 Angstroms; this property enables the separation of the reflections of montmorillonite and illite on the diffraction pattern. The heating process results in a distinguished peak at 14 Å when chlorite is present.

The relative amounts of the three major clay minerals were estimated by means of a method used in previous work of the Research Council of Alberta. This method is based on the same principles as the one proposed by Johns, Grim and Bradley in 1954. The integrated intensities of a characteristic reflection above the background level is taken as a measure of the abundance of a specific mineral constituent. Due to the fact that the scattering of the reflections on the diffraction pattern is dependent on the angle of incidence, the integrated intensities have to be multiplied by a certain factor, before computing the relative amounts of each clay mineral. Thus the area below the kaolinite reflection at 7 Å (glycol saturated sample) is multiplied by 1.6 and the integrated intensity of illite at 10 Å by 4 before compared with the reflection of montmorillonite at 17 Å.

This method of quantitative analysis is considered to be crude

but reasonably sound in its approach, as will be discussed later.

Test results are presented in TABLE XI. Only the major clay minerals, kaolinite, illite and montmorillonite were considered. In five tests a small amount of chlorite was identified and included in the percentage given for kaolinite.

5:3 Summary of Soil Science Tests

TABLES VIII, IXa and IXb summarize the results obtained from standard soil science tests. The classification itself is based on the mechanical analysis (grain size analysis). The determination of the exchangeable cations and electrical conductivity serves to identify and characterize the various soil series and horizons and, to the soil scientist, gives information about the properties of the soil in relation to plant growth and fertilizer problems. The presence of salts in the soil was revealed by the analysis of the cation exchange complex as well as conductivity measurements of saturation extracts.

The salt content variation with depth showed characteristic changes from B- to C-horizon. Identification and quantitative analysis of clay minerals were obtained from an interpretation of X-ray diffraction patterns of natural, glycol saturated and heated soil.

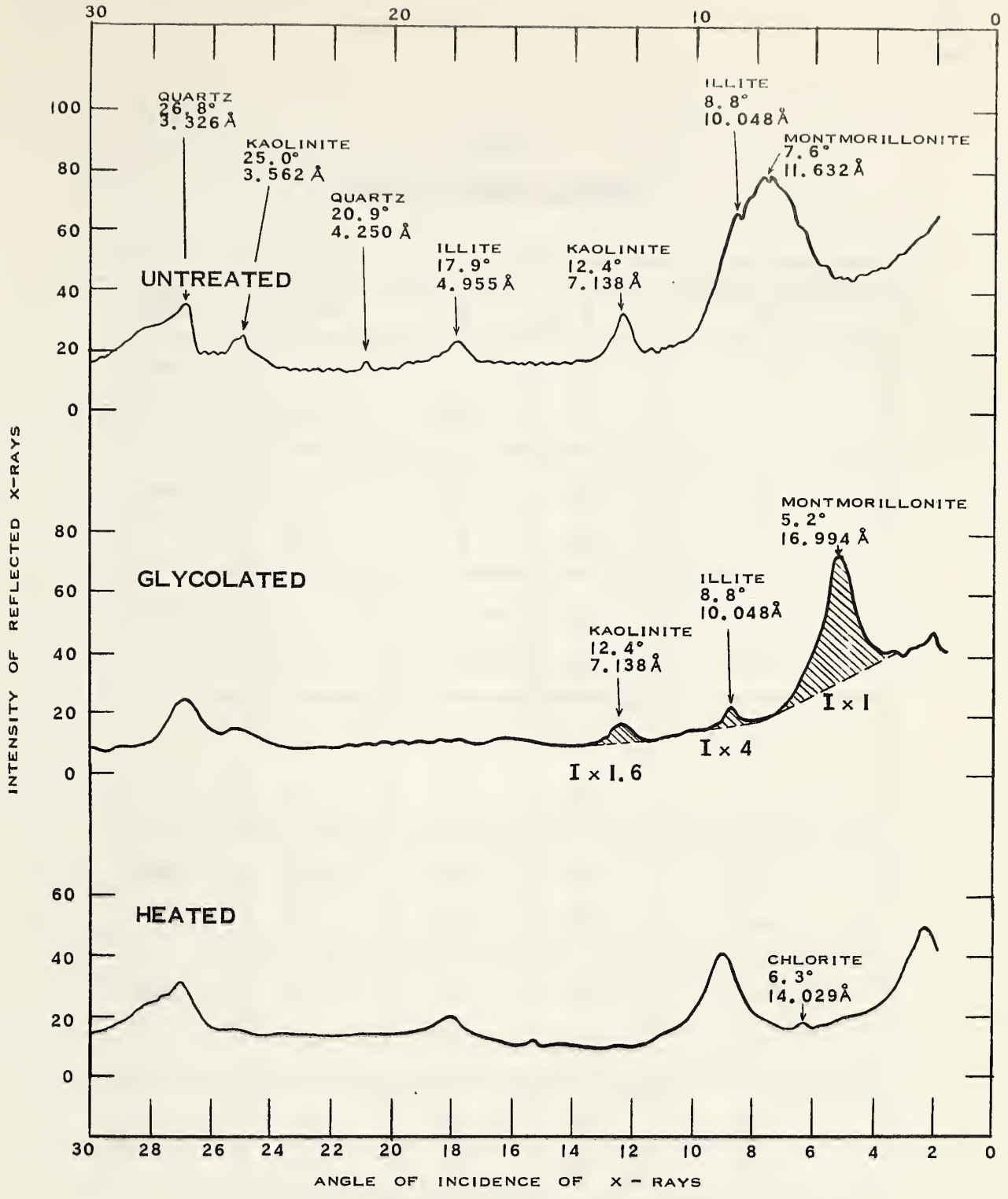


FIGURE 17. – X - RAY SPECTROMETER TRACES OF 0.002 MM FRACTION OF WETASKIWIN SOIL [B - HORIZON] IN AIR - DRIED STATE, FOLLOWING TREATMENT WITH GLYCOL AND HEATING TO 450 °C.

TABLE XI

ANALYSIS OF CLAY MINERALS

SOIL TYPE		Material Finer	Kaolinite %	Illite %	Montmorillonite %
Wkn.	B	2μ	7 *	16	77
		1μ	10	13	77
Wkn.	C	2μ	10	20	70
		1μ	9	15	76
Nv.	B	2μ	8 *	17	75
		1μ	12 *	23	65
Nv.	C	2μ	9	13	78
		1μ	9	14	77
Cam.	B	2μ	13	42	45
		1μ	13	43	44
Cam.	C	2μ	7	14	79
		1μ	11	16	73
Ar.	B	2μ	16 *	47	37
		1μ	18	45	37
Ar.	C	2μ	9 *	14	77
		1μ	9	11	80

* small amount of chlorite present and included in this figure.

CHAPTER VI

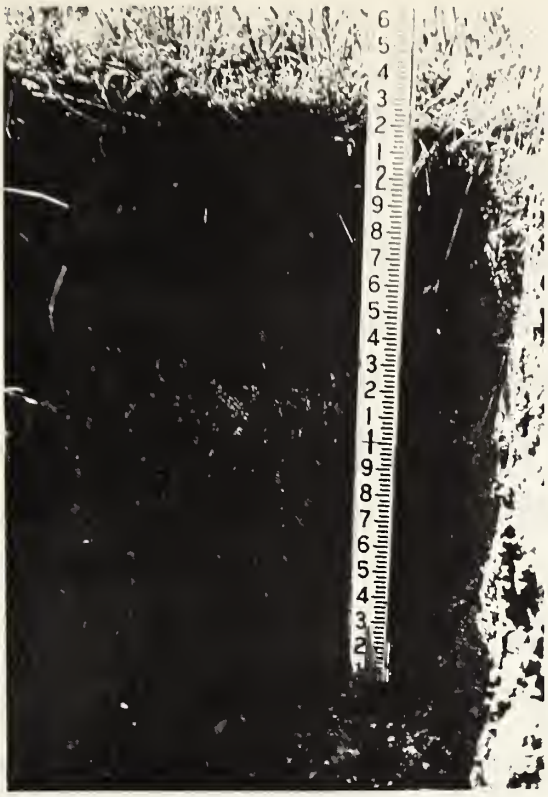
DISCUSSION

6:1 Characteristics of the Soil Series

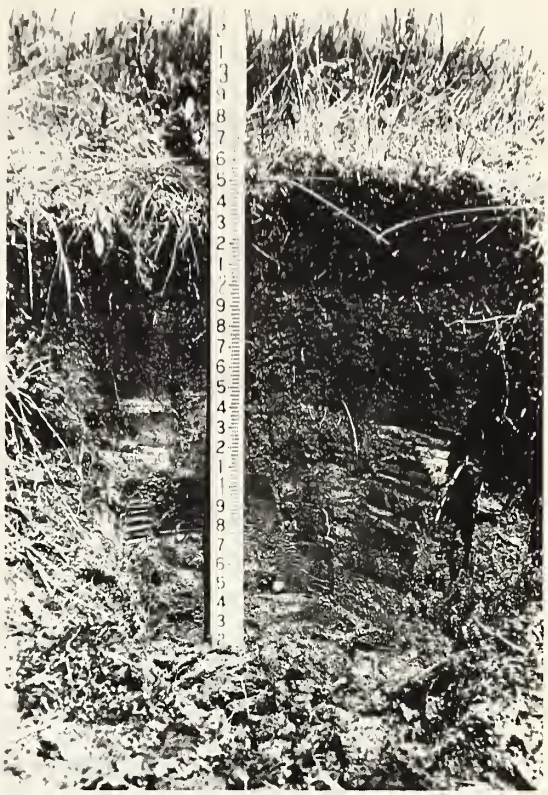
Before discussing the test results, it is of interest to see if the soil sampled has the structural and chemical properties expected. For this purpose some of the Soil Science classification test results are compared with information given in the Alberta Soil Survey Reports No. 14 (Peace Hills Sheet, 1947) and No. 21 (Edmonton Sheet, 1962) and partially described in Section 3:1 of this report.

6:1:1 Wetaskiwin

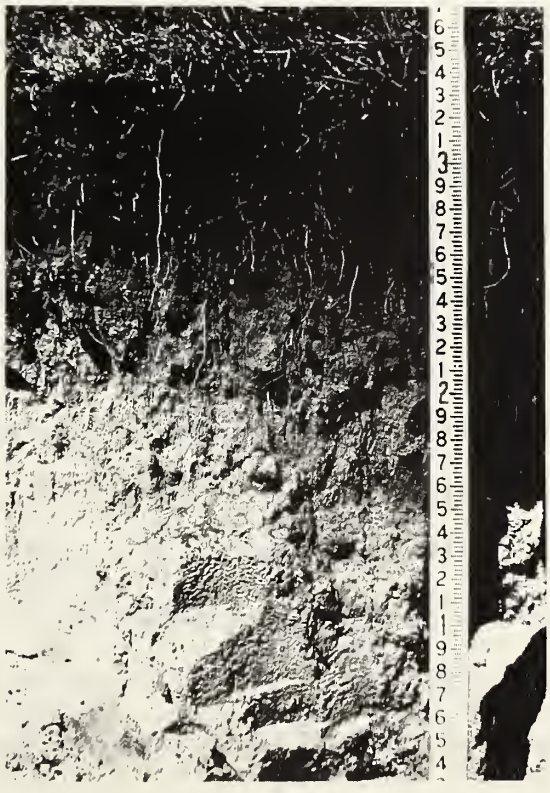
Wetaskiwin soil was sampled a few miles south east of the City of Wetaskiwin (SE 15 TP 45 R 23). The Soil Survey describes the B-horizon as very dark brown clay, heavily stained, columnar with flat to rounded tops, hard medium blocky mesostructure. The C-horizon is brown to dark brown, stone free, massive clay, containing some lime and salt. These characteristics do not show up very well on PLATE 3A since this photograph was taken under unfavourable light and moisture conditions. However, PLATE 3A shows the heavy accumulation of salts in the upper part of the C-horizon (1 foot below surface), which is characteristic for a solonetzic soil. The B-horizon is confined to about 0.8 feet. On drying the high amount of crystallized salt causes the C-material to break down more readily in small particles of irregular shape.



[A] WETASKIWIN



[B] NAVARRE



[C] CAMROSE

[D] ANGUS RIDGE

SOIL PROFILES

PLATE 3

The chemical analysis (TABLE IXa and b) showed that the predominant exchangeable cation is Ca(40-63%). Na constitutes 10 to 28% of the exchangeable cations. In the average more than 15% of the exchange capacity is occupied by Na. According to Winterkorn (1953), as quoted by P.A. Thomson (1960) as little as 15% of Na is enough to give montmorillonite the properties of a homionic Na-montmorillonite. Therefore one might say that Wetaskiwin represents a Na-clay, although Na is not the predominant exchangeable cation.

TABLE VI shows that the salt concentration in the C-horizon is considerably higher than in the B-horizon. Having in mind the values for the exchange complex and salt content, the Wetaskiwin soil can be said suitable for the purposes of this investigation.

6:1:2 Camrose

The Camrose soil was sampled at a location about 17 miles east of Elk Island Park beside Highway 16. The Camrose profile is similar in solum characteristics to the Wetaskiwin profile, the principal difference being the mode of deposition of the parent material. PLATE 3C shows a photograph of the Camrose profile. At a depth of about 1 ft. lies a transition zone from the A- to the B-horizon. The C-horizon starts at about 2 ft. below surface. Pure B-horizon extends over approximately 0.8 ft. The percentages of the various exchangeable cations (TABLE IXb) and the amount of soluble salts (TABLE VI) is comparable to the Wetaskiwin. The total exchange capacity of Camrose, however, is considerably lower than Wetaskiwin. This is associated with a much lower clay content of the Camrose soil (TABLES III and VIII) and leads to a different classification:

Camrose is classified as a clay loam (Soil Science) or clay of low plasticity (CL, according to U.S.C.S.) and Wetaskiwin as a heavy clay or clay with high plasticity (CH).

Therefore, in comparing Camrose and Wetaskiwin soil, one has to keep in mind that they are a different type. Although Na is not the predominant exchangeable cation, Camrose could be called a Na-soil , based on the same considerations as outlined for Wetaskiwin.

6:1:3 Navarre

Navarre soil was sampled in the same area as Wetaskiwin soil (exact location SE 15 TP 45 R 23). Navarre loam is distinguished by a deep black surface layer (PLATE 3B). The B-horizon material breaks into small uniform to granular mesostructure. The salt concentration in the C-horizon may vary with the natural or artificial drainage found in the area.

The soil sampled shows a considerably lower content of soluble salts than the solonetzic soils discussed previously. The amount of exchangeable Na ranges from about 2 to 7%, while exchangeable calcium amounts to 56 to 73%. Therefore the Navarre soil may be called a Ca-soil.

Total exchange capacity and clay content are in the order of magnitude of Wetaskiwin soil. This will allow some qualitative comparisons between Wetaskiwin and Navarre soil.

6:1:4 Angus Ridge

Chemical analysis (TABLE IX) and determination of salt content (TABLE VI) show that the soil sampled as Angus Ridge does not show

characteristics significantly different from Camrose. This may be explained by the fact that these soils were sampled only about 30 feet apart. The photographs (PLATE 3C and D), however, show that we are dealing with different types of profile.

The lower part of the A-horizon of Angus Ridge, extending to about 1.2 ft. below surface, is much lighter coloured than the upper part and the hard columnar to blocky B-horizon has white-capped rounded tops. According to Bowser (1961) these are characteristics of a solodized solonetz. (With continued leaching, a process of de-alkalization or solodization takes place and the solonetz becomes a solodized solonetz.) The Alberta Soil Survey Reports No. 14 (1947) and No. 21 (1962) mention that the Angus Ridge profile may tend to have characteristics of a solod. For the purposes of this investigation it was hoped to get a soil with a very low salt content and a low Na-percentage in the exchange complex. This is, however, not the case. The effect of crystallized salt on the structure of air dried material from the C- as compared to the B-horizon is illustrated on PLATE 4B: C-material breaks more readily in small particles of irregular size and shape.

6:1:5 Summary

Four soil series were chosen for this investigation. Wetaskiwin and Camrose may be expected to show characteristics of a Na-soil with a lower and higher salt content (B- and C-horizon, respectively). Navarre may tend to show characteristics of a Ca-soil. Angus Ridge will have properties similar to those of the Camrose soil. The chemical analysis of Malmo soil (results obtained from the Alberta Research Council) suggests

that this soil has characteristics of a true Ca-soil with a very low salt content.

Pictures illustrating the soil profiles are shown on PLATE 3.

6:2 Engineering Properties

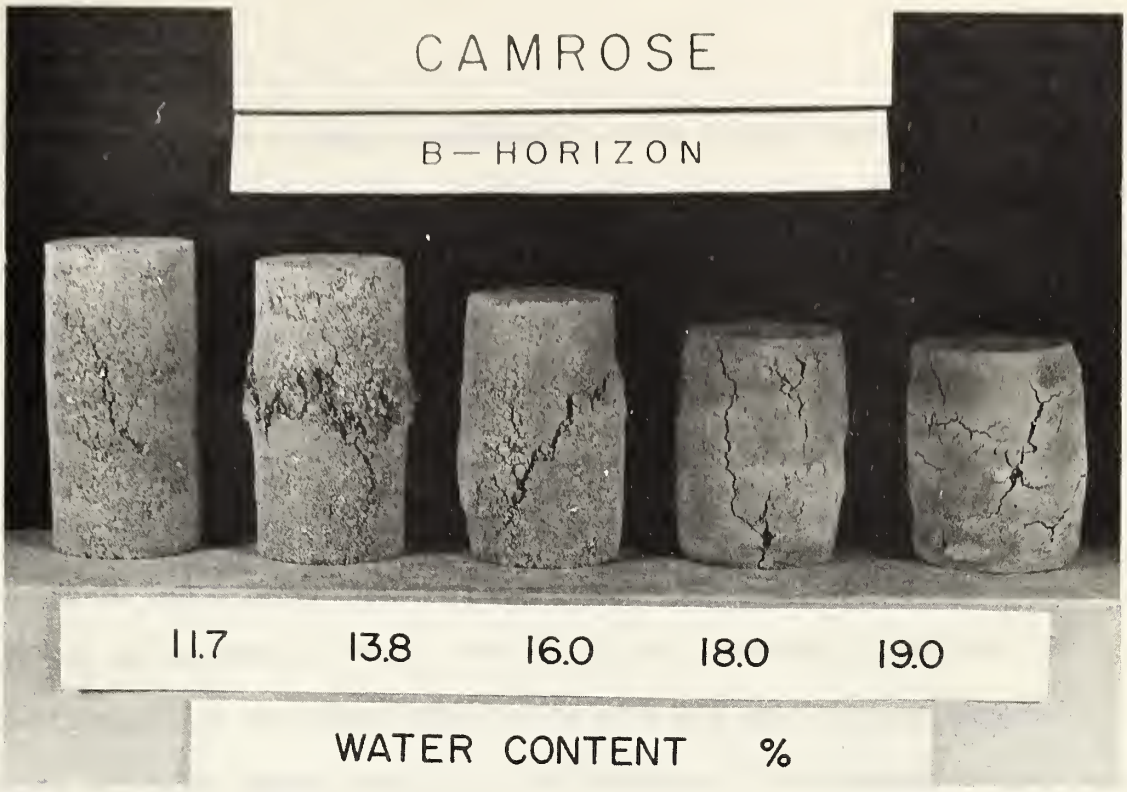
Under this heading, results of standard engineering tests are discussed. It will be of interest to see whether there are any changes in soil properties from B- to C-horizon and, in case there are some differences, whether there is a consistent trend in these variations or not.

6:2:1 Classification Test Results

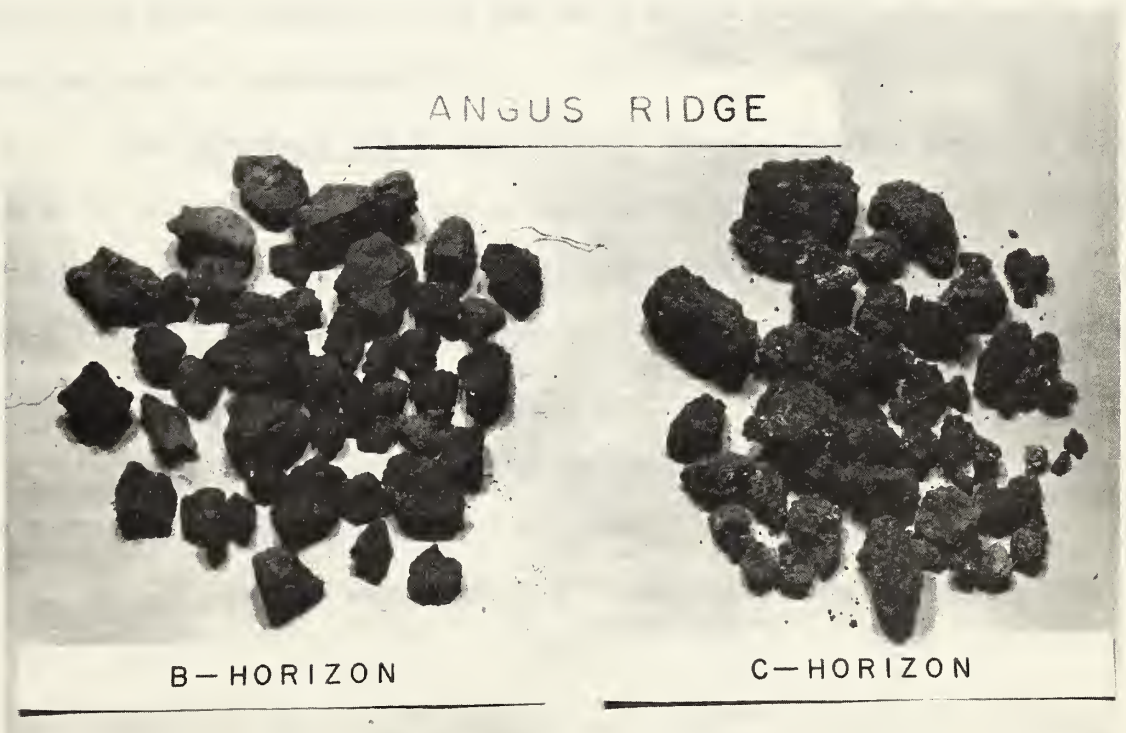
Test results are given numerically in TABLE III. A graphical representation of liquid and plastic limit, flow index, specific gravity and shrinkage limit values is shown in FIG. 18.

The Atterberg limits do not seem to differentiate consistently between B- and C-horizon. A maximum difference of 9% in liquid limit between B- and C-material was found for the highly plastic Navarre soils.

The flow index, as shown in FIG. 18, revealed a consistent increase from B- to C-horizon in all soil profiles investigated. The flow index I_f can be interpreted as a measure of the rate of change in strength with change in moisture content, the strength being a function of the number of blows necessary to close the standard groove used in the procedure to determine the liquid limit. The value I_f was believed to be related to the unconfined compressive strength index I_q as defined in Chapter IV (4:1:7), which describes the change of unconfined compressive strength with



[A] UNCONFINED COMPRESSION TEST SAMPLES



[B] STRUCTURE OF ANGUS RIDGE SOIL

PLATE 4

moisture content in a range considerably below liquid limit, but above optimum moisture content. However, the I_q values rather decreased than increased from the B- to C-horizon, as contrary to I_f values. The determination of the unconfined compressive strength will be discussed further in a subsequent section.

Examination of the tan B value, which is reported to average 0.100 for Canadian soils (Eden, W.T.) disclosed considerable variation, as shown in TABLE III. The solonetzic soils, Wetaskiwin and Camrose, indicated an increase of tan B from the B- to C-horizon of 46% and 72% respectively; on the other side, soils with low salt content such as Navarre and Malmo showed negligible differences. This suggested that tan B increases with salt content. Values of tan B computed from data of G. Locker (1963) are given in TABLE XII. Results of the Ca-modifications seem to support the above finding, while the tan B of the Na-soils do not show any trend and scatter considerably.

The shrinkage limit (see FIG. 18) shows a general trend to increase from B- to C-horizons. This indicates that volume changes due to fluctuations in moisture content in the range below the plastic limit are more severe in the B-horizon. This probably contributes to the generally more blocky and columnar structure of the B-horizon.

The effect of salts on the shrinkage limit is demonstrated in the following tests performed by the author:

A paste of Wetaskiwin B soil with artificially reduced

TABLE XII

TAN B OF HOMIONIC MODIFICATIONS

OF EDMONTON CLAY

(Computed from data of G. Locker, 1963)

Predominant exchangeable cation	I_f	tan B	S.C. me/100 g.a.d.s.
Ca	13.2	0.071	13.0
Ca	15.3	0.084	18.9
Ca	18.4	0.116	68.3
Na	15.9	0.073	0
Na	7.8	0.043	2.3
Na	6.5	0.039	4.7
Na	16.1	0.095	7.6
Na	10.0	0.061	13.1

S.C. = salt content, computed from TEC and amount of exch. cations.

a.d.s. = air dried soil.

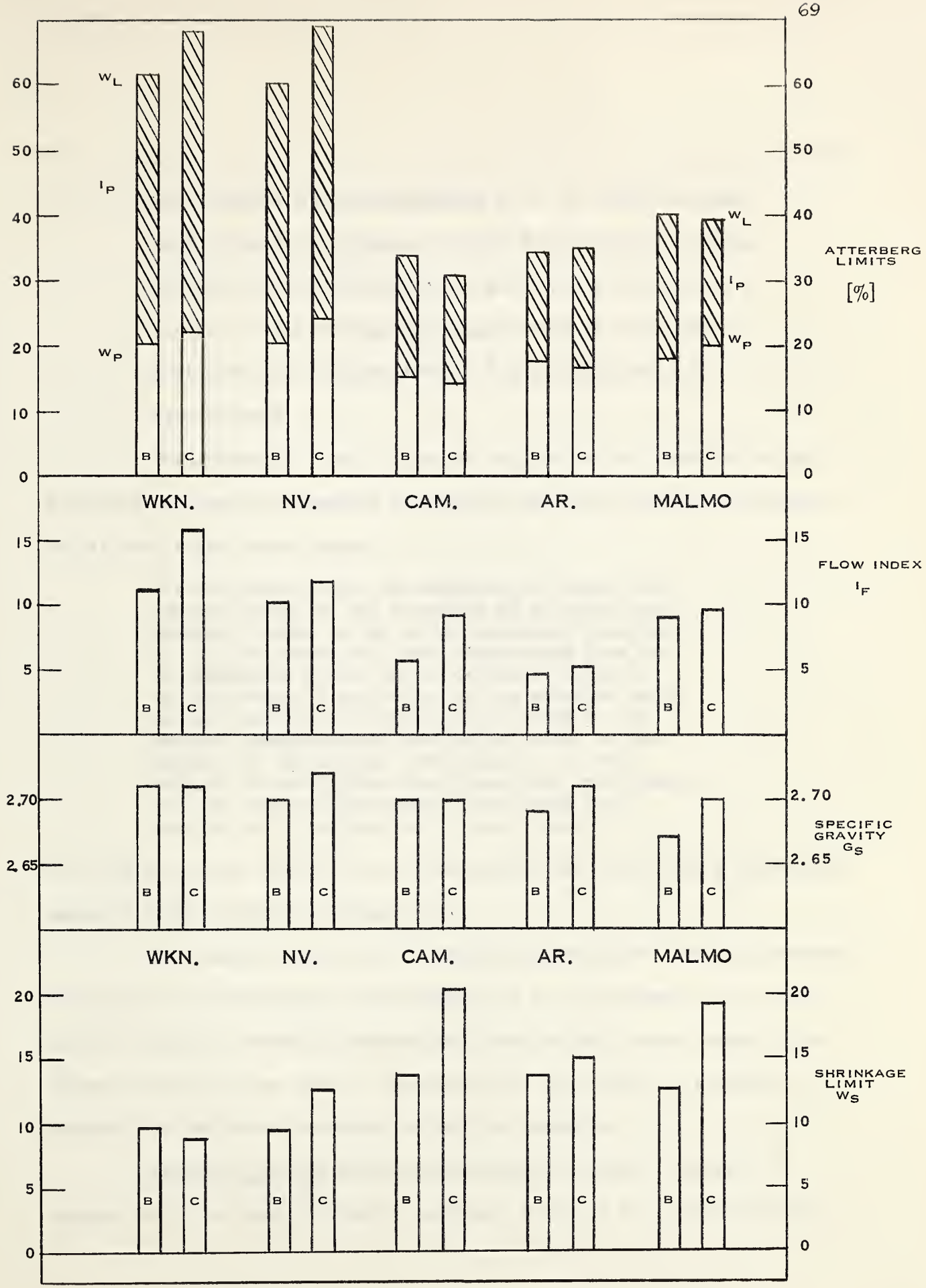
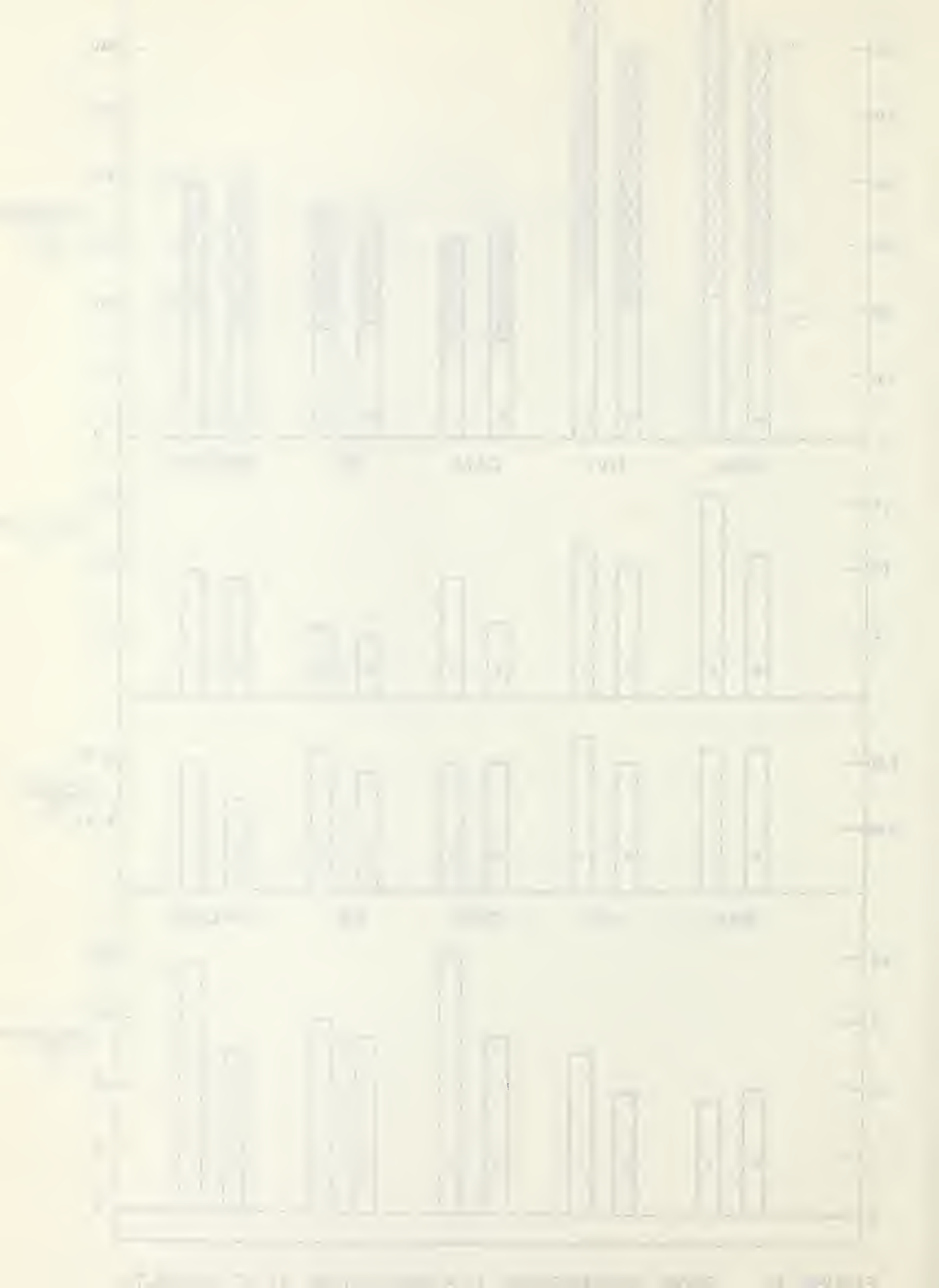


FIGURE 18. – SOME ENGINEERING CLASSIFICATION TEST RESULTS.



salt content and passed through a No. 40 sieve was made up at a moisture content of about 80% with the following liquids: distilled water, 0.5 molar and 5 molar $CaCl_2$ solution. The average shrinkage limits of these three modifications were found to be 8.4%, 10.8% and 15.7% respectively.

The effect of salts (either in solution or as crystals) on soil structure has been discussed by Di Martino (1961) who stated, in relation to his Pellicular Water Theory:

> "It is probable that the coherence of dried soil samples is due to the formation of a crystalline skeleton formed by the salts previously dissolved in the free water and then concentrated from the intergranular annula to the points of contact; the existence of salts also in the adsorbed water as well as in the external films, gives to the whole a chemo-physical continuity which, in the absence of the solvent (free water), can well explain the mechanical resistance, the brittleness and the lack of thixotropy of the dried soil samples or, in nature, of the soil clods."

It is felt that the effect of salts in crystalline form on soil properties would be worth further investigations.

In connection with the discussion of the differences in structure as apparent from shrinkage limit results, it is of interest to note that natural moisture retention capacity, as shown in FIG. 16a-d, seems to be lower in the B-horizon than in the C-horizon. This again, illustrates somewhat the different structure of the two horizons.

Specific gravity values as contained in TABLE I and FIG. 18 suggest that the specific gravity increases from the B- to the C-horizon.

This fact has been explained by S. Thomson (1963, p.37) who concludes his discussion with the following statement:

> "The presence of soluble salts in the pore water increases the observed value of the specific gravity of the soil solids."

If a certain amount of soil contains soluble salts, the volume of displaced water in the pycnometer per weight of air-dry soil is reduced compared to the same soil without salts. This causes an increase in the computed value of the specific gravity. It is felt that the observed slight changes in the exchange complex of a soil between B- and C-horizon do not affect the specific gravity significantly.

The grain size analysis and determination of the percentage finer than 0.002 mm. will be discussed later in this chapter, comprising soil science and engineering procedures.

6:2:2 Compaction Characteristics

TABLE IV and FIG. 3 show that there may be a considerable difference in optimum moisture content and maximum density between material from the B- and C-horizon. A maximum difference of 4% in optimum moisture content (Wkn.) and 4.6 lbs/ft^3 in maximum density (Malmo) was found in this test series. This finding has its immediate application to highway engineering. It indicates that the optimum moisture content in the same area may vary several percent depending whether the subsoil consists of soil from B- or C-horizon.

No definite trend was observed in compaction characteristics of B- compared to C-horizon, as illustrated by FIG. 19.

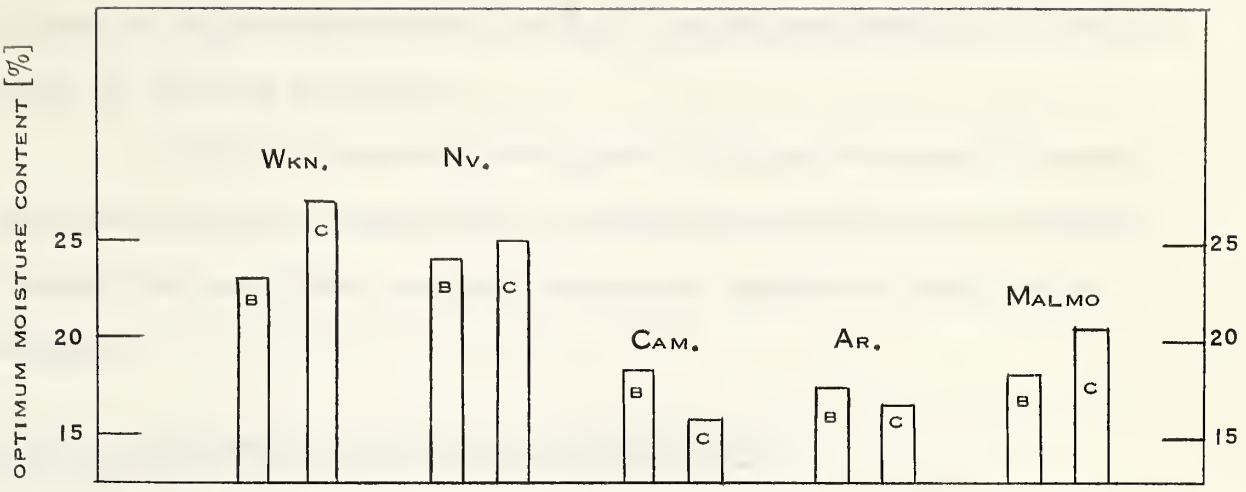


FIGURE 19. – OPTIMUM MOISTURE CONTENT OF VARIOUS SOIL PROFILES.

6:2:3 Strength Properties

As the compaction characteristics vary considerably within a short part of the soil profile, so do strength properties; this fact is illustrated in FIG. 7 to 10. It was found that a straight line relationship between strength and moisture content on a semi-logarithmic plot could only be established in the range above optimum moisture content, where the degree of saturation of the compacted samples was between 85 and 95%.

S. Thomson (1963, p.96) observed that the slope of the log pressure-void ratio curve is affected by the salt content in the pore water.

Values of I_q (TABLE IV), representing the slope of the log strength-moisture content curve, show a slight tendency to decrease from

the B- to the C-horizon. This would be in accordance with flatter slopes for higher salt contents of Na, Ca and Mg modifications of Edmonton clay, as reported by Thomson.

PLATE 4a illustrates the types of failure observed at various moisture contents of Camrose soil. Failure may take place in a definite diagonal failure plane, through a horizontal compaction plane, or by bulging.

6:2:4 Consolidation and Swelling Characteristics

The e-log p curves from B- and C-horizon of the Wetaskiwin soil profile are very similar in shape, however the void ratios obtained under the same pressure is consistently lower in the B-horizon. Generally lower void ratios were found in B- than in C-material when subjected to the same pressure, the difference becoming smaller at higher pressures. This tendency is revealed in the compressive index (TABLE V) determined for each soil, which was found to be either the same or increasing from B- to C-horizon. The rebound curves did not indicate any significant changes or trends in relation to the soil profile.

The coefficient of consolidation and permeability as calculated by means of Terzaghi's theory of consolidation were found to vary considerably; however no trends could be established.

An interesting phenomena was observed when the electric conductivity of the pan water after the completed consolidation test was measured. The conductivity of the original distilled water was approximately 5 micromhos/cm; in the case of Camrose C-horizon soil, the conductivity increased due to dissolution of salts from the soil to a

value of 2300 micromhos/cm. The salt rich C-horizon can be distinguished from the B-horizon by means of these measurements, as readily seen in TABLE V.

Due to the escape of salty pore water, a decrease in dry weight of the entire sample during the consolidation test may occur and amount to 1-2% of the initial dry weight. This can produce an equivalent error in determining the moisture content.

In order to further investigate the effect of soluble salts on consolidation characteristics, a few special tests were performed.

Wetaskiwin B-soil, the salts of which were partly removed by leaching, was prepared at a moisture content of about 80%, using the following liquids: distilled water, 0.5 and 5 molar $CaCl_2$ solution and 0.5 molar CaAc solution. The pan of each Wykham-Farrance consolidometer was filled with the corresponding fluid before starting the test. Pertinent results are given in the following TABLE XIII.

TABLE XIII

CONSOLIDATION OF WKN. B IN DIST. WATER AND Ca-SALT SOLUTIONS

Wkn. B in solution of	C_c load increment 1-10 kg/cm^2	c_v at e = .9 (cm^2/sec) x10^{-4}	k at e = .9 (cm/sec) x10^{-9}	t_{100} at 7.82 kg/cm^2 (min)	EC of pan water at end of test (micromhos/cm)
Dist. H_2O	0.49	0.60	2.0	150	450
0.5 M $CaCl_2$	0.46	2.00	7.6	68	> *
5M $CaCl_2$	0.48	3.22	15.0	58	>
0 5 M CaAc	0.52	1 33	5.2	24	>

EC = Electrical Conductivity
* beyond capacity of conductivity bridge used (10,000)

As it may be seen from these results, the compressive index C_c did not experience an appreciable change due to the presence of salts. However the coefficient of consolidation c_v and the permeability showed a consistent increase with salt concentration. The results obtained with a $CaCl_2$ solution are reasonably well within the range of the values for a CaAc solution at corresponding concentration, indicating that the type of anion seems to be less decisive in influencing the consolidation properties of this soil than the concentration of the solution. The study of the rebound branch of the e-log P curve of the various modifications (FIG. 20) disclosed a remarkable effect of soluble salts on the swelling of remoulded soil.

As previously observed by Ladd (1960) on compacted soil soaked in $CaCl_2$ solutions, the presence of Ca-ions in the pore water reduces the amount of swelling considerably. It should be noted, that the fluid available for rebound in the tests performed by the author can be assumed to be of the same concentration as the pore water already present in the soil sample before reducing the surcharge. Thus, any physico-chemical effects due to different concentration of external (pan water) and internal (pore water) fluid are excluded and the variation in rebound behaviour of the soil would have to be explained considering cation exchange and effect of salts on intracrystalline and interparticle bonds.

Comparing TABLE XIII with TABLE V it can be seen that the difference in salt concentration in the B- and C-horizon is not the main factor in determining consolidation and swelling characteristics of these soils, since coefficient of consolidation and permeability may be lower in

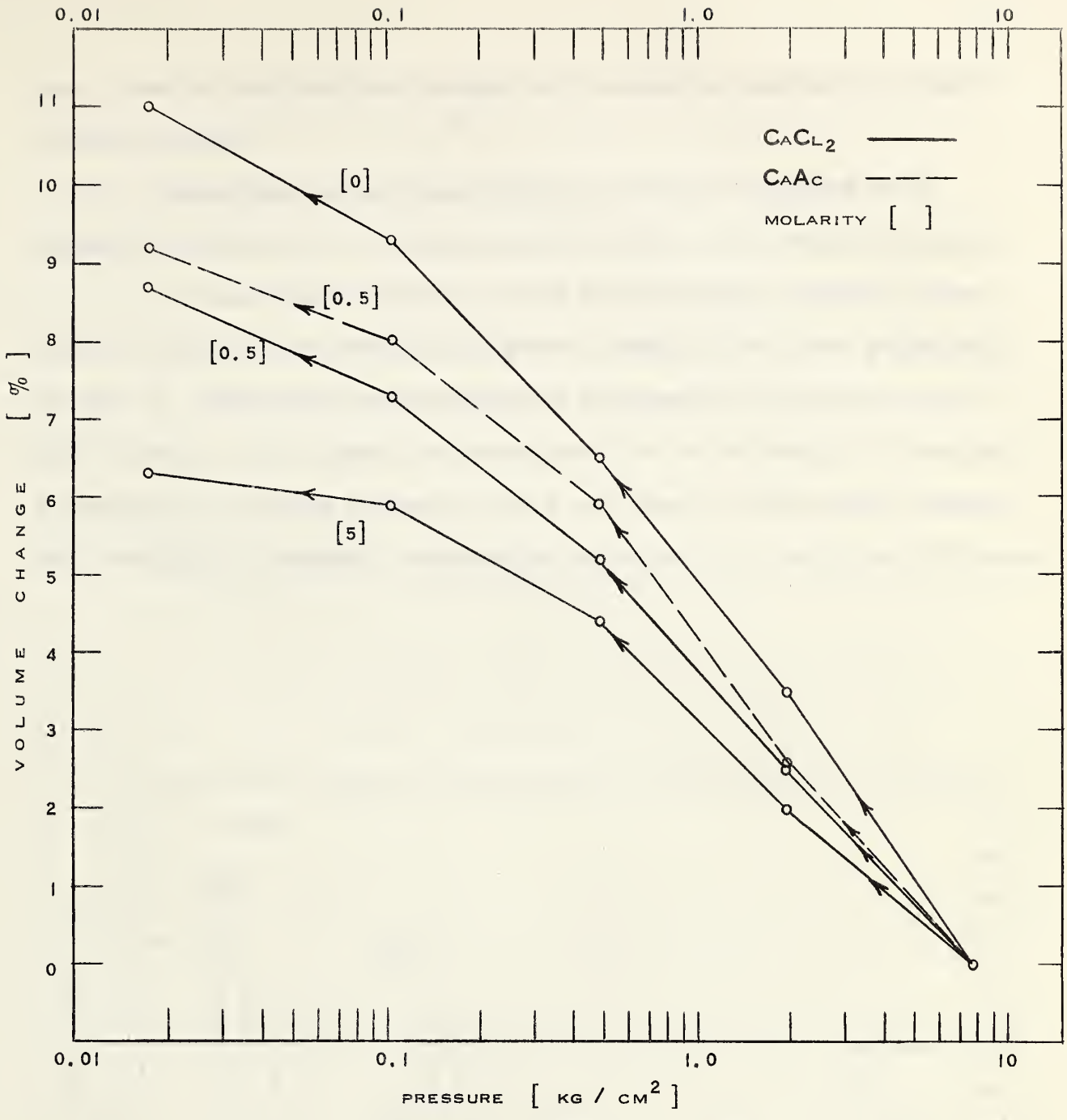


FIGURE 20. – REBOUND CURVE OF WETASKIWIN SOIL, B - HORIZON, CONSOLIDATED IN DISTILLED WATER AND VARIOUS CALCIUM SALT SOLUTIONS.

the C- than in the B-horizon, whereas salt content is considerably greater in the C-horizon.

Consolidation test results will be further considered in an attempt to interpret soil properties on the basis of the theory of osmosis.

Of considerable practical value for the highway engineer is the value of the swelling potential, as given in TABLE IV and shown graphically in FIG. 21. The results show significant differences in properties of B- and C-horizon. If a highway is placed partly on B- and partly on C-horizon, differences in swelling properties could well lead to differential movement and cracking of a pavement, provided the B-horizon is of sufficient thickness.

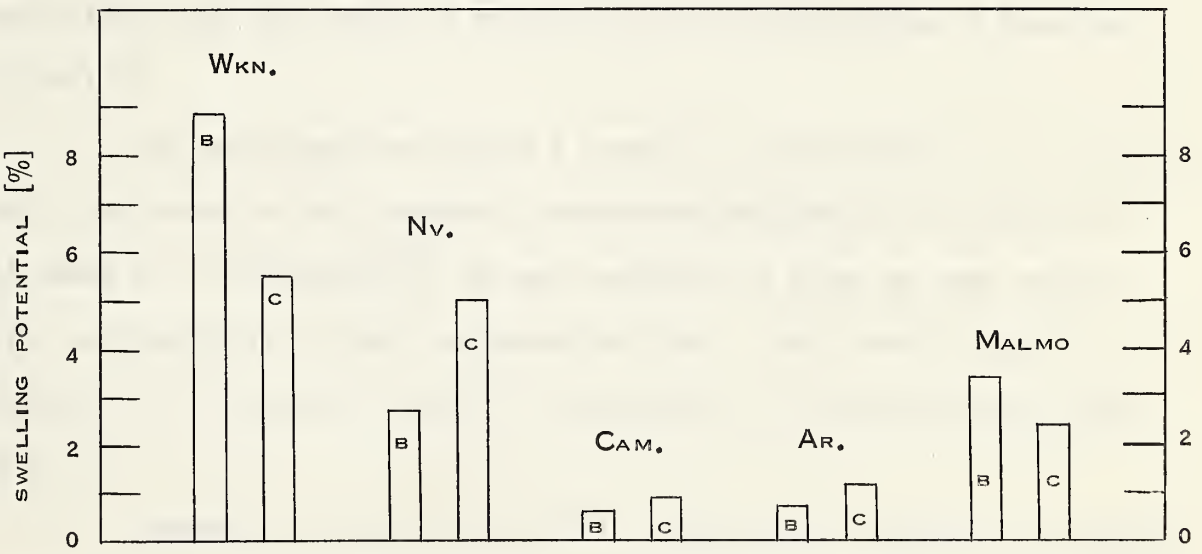


FIGURE 21. – SWELLING POTENTIAL VARIATION IN SOME SOIL PROFILES.

It is felt that the value of the swelling potential is not suitable for quantitative analysis on a physico-chemical basis, since its value depends on test conditions. The swelling potential is measured at a different moisture content for various soils and under one specific surcharge. That initial void ratio, dry density and surcharge load are of utmost importance when considering the swelling of a soil has been shown clearly by Gilchrist (1963), who examined the volume change properties of Regina clay.

6:2:5 Summary

Liquid limit, plasticity index and plastic limit of B- and C-horizon of a soil profile might vary considerably, but no general trend in variation is evident. The flow index increased consistently from B- to C-horizon. Tan B disclosed considerable variation and there are indications that this value is affected by the concentration of Ca-salts in the soil.

The shrinkage limit shows a trend to increase from B- to C-horizons. This is believed to be a measure of structural properties of these soils and seems to be influenced by the salt content, as shown by some special tests with addition of $CaCl_2$ to Wetaskiwin soil. The specific gravity, as measured by the pycnometer method, also appears to be affected by soluble salts.

Compaction tests indicated that considerable variation in optimum moisture content and maximum density might occur within a single soil profile. Standard Proctor and Miniature Harvard tests yielded similar differences in properties of B- and C-horizons.

Comparison of consolidation test results of three soil profiles with results obtained for one soil consolidated in Ca-salt solutions of various concentration indicate that soluble salt is not the main factor in determining consolidation and swelling characteristics of B- and C-horizon of a soil series.

Significant differences in the swelling potential of B- and C-horizon were found. Although no general trend was observed, this finding might be of practical value for a highway engineer.

6:3 Some Major Properties as Evaluated by the Engineer and Soil Scientist

6:3:1 Clay Content

Engineering properties of a soil are known to be strongly affected by the clay content, therefore the determination of the amount of clay is of utmost importance. A standard testing procedure is likely to give only a relative measure of the clay content which is often sufficient for the interpretation of test results or assessing engineering properties of a soil. However, for research purposes, not only the use of any "standard" procedure, but also the definition of the clay sizes as 0.002 mm may be questioned. Rather different results were obtained by means of the hydrometer and pipette test, both representing a grain size analysis based on the sedimentation principle. In TABLE XIV, results from TABLES III and VIII are compared.

TABLE XIV

CLAY CONTENT DETERMINATIONS

		% Clay-Hydrometer	△ B-C	% Clay-Pipette	△ B-C
Wkn.	B	51	9	73	3
	C	60		76	
Nv.	B	49	13	85	-1
	C	62		84	
Cam.	B	17	-3	35	-5
	C	14		30	
Ar.	B	12	0	32	-3
	C	12		29	

It is apparent that the more vigorous pre-treatment of the pipette test causes an increase in the percentage of fine particles. The Soil Science pipette procedure is distinguished by the leaching out of soluble salts prior to the sedimentation test and by a longer time of dispersion in the mixer. Remembering statements by West and Jones (1961) the difference between pipette and hydrometer results for the more silty soils (Cam. and Ar.) may be attributed to the longer mechanical dispersion, while for clay soils (Wkn. and Nv.) the effects of chemical dispersing agent and soluble salts in the soil must be considered.

There does not seem to be a definite trend in the variation of clay content from the B- to the C-horizon. However, the differences obtained by a standard procedure on B- and C-material are in the same

order of magnitude as differences due to pre-treatment and varying amount of dispersing agent. TABLE VI shows a definite relation between salt content (or electrical conductivity) and flocculation characteristics of a soil-water suspension.

To be more reliable, pipette tests should be run in duplicate since the determination of the percentages of clay and fine clay relies on weighings in the order of magnitude of 10 mg and therefore is very sensitive to procedural errors.

6:3:2 Salt Content

The original and, to some extent, the direct source of all the salt constituents are the primary minerals found in soils and in the exposed rocks of the earth's crust (U.S. Dept. of Agriculture Handbook No. 60). During the process of chemical weathering, which involves hydrolysis, hydration, solution, oxidation, and carbonation, these constituents are gradually released and made soluble. Saline soils usually occur in areas that receive salts from other locations, and surface and ground water is the primary carrier. According to Bowser (1961), the most common salts in the soils of Western Canada are the sulphates of sodium, magnesium potassium, and calcium; carbonates, bicarbonates, and chlorides may also be present in small amounts.

Results of the evaluation of the salt content are given in TABLE VI. FIG. 14 shows that the mild treatment of the filtrate with HCl, in order to reduce the amount of colloidal matter, decreases the scatter of the plot EC versus salt content in p.p.m. Comparison of FIG. 14 with FIG. 22 shows that the results obtained plot within the range of EC

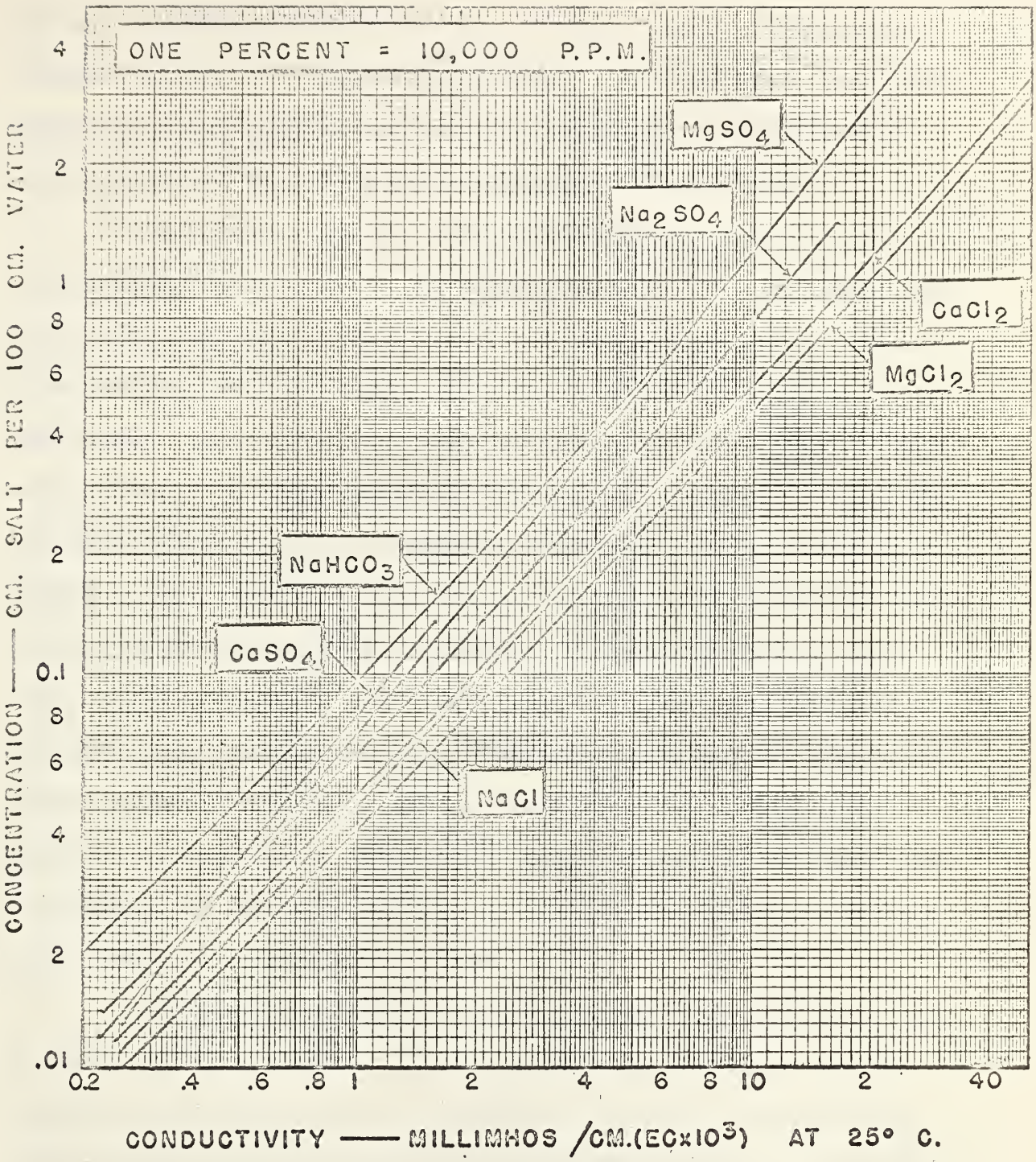


FIGURE 22. – CONCENTRATION OF SINGLE SALT SOLUTIONS IN PERCENT AS RELATED TO ELECTRICAL CONDUCTIVITY.

[FROM U. S. DEPT. OF AGRICULTURE , HANDBOOK NO. 60]

and salt concentration values as found by the U.S. Dept. of Agriculture (Handbook No. 60) for single-salt solutions It is felt that the EC value might give a more reliable indication in evaluating the properties of saline soils than the determination of soluble salts by weight.

The effect of soluble salts on the engineering properties investigated in this report is not readily apparent. The soil-water ratio in the hydrometer test is usually 1:20, in the specific gravity test 1:10; in determining Atterberg limits and in the field the ratio may be 2:1 or even higher. There is no doubt that the effects of salts depend on their concentration. The above considerations show that relations between test and field properties may be obscured by the effect of salts occurring in different concentrations. Another fact, which has to be considered, is the limited solubility of salts in water. A suspension of Wkn. C-soil (ratio 1:20) was found to have a salt content of 976 p.p.m. (TABLE VI). The salt content in the pore water of this soil at a moisture content of 50% would therefore theoretically be 39,040 p.p.m. According to the Handbook of Chemistry and Physics this concentration would be higher than, for example, the solubility of $MgSO_4$ in cold water (= 26,000 p.p.m.) and part of the salt would crystallize out.

Test results in TABLE VI show that there is a definite increase in soluble salts from the B- to the C-horizon. Together with varying clay content this might lead to considerable differences in engineering properties of B- and C-horizon, as it has already been shown. In previous research at the University of Alberta (S. Thomson and Locker) the salt concentration in the pore water was evaluated by computing the difference

between the sum of the exchangeable cations, Ca, Mg, Na, K and the total exchange capacity. Examination of TABLE IXa (column 7) shows that this method cannot be applied successfully to the work of this report since the values Σcations-TEC scatter too much. It is felt that this method of evaluating salt content was only justified for homionic soils as tested by S. Thomson and Locker (1963). Electrical conductivity measurements on a saturation extract seem to give more consistent results and a better evaluation of the salt content. It may also be pointed out that the total exchange capacity is measured by a titration, while individual cations are determined by means of the flame photometer. A titration is very likely to give different results depending on the technician and the chemical indicator used. Therefore, it is felt that the Σcations-TEC does not give a reliable value for the salt concentration.

Success of future research on saline soils will depend on whether a reliable method of evaluating soluble salts is used or not. None of the three methods used in this investigation is felt to be entirely satisfactory. Evaluation of soluble salts from data of the cation complex is not reliable for soils with an unknown variety of exchangeable cations. Determination of soluble constituents by weight is very sensitive to procedural errors; adsorption of air moisture (as illustrated by TABLE VII) disturbs the weighing and not all colloids can be filtered out by normal fine paper or ceramic filters (compare results of Series 1 and Series 2 in TABLE VI). The electrical conductivity is perhaps the best evaluation of the effective salt content; however, it cannot be related accurately to salt concentration in p.p.m. when the type of salt is not known.

PLATE 2B is a photograph of the residue found at the bottom of a 250 ml beaker after evaporating the filtrated liquid from a suspension of Cam. C soil (Test Series No. 2). An interesting crystallization has taken place in the final stages of water evaporation.

6:3:3 Organic Matter

In discussing chemical tests carried out in engineering soil testing, Ackroyd (1957) states:

> "The difficulty in measuring the organic content is that the organic matter is derived from a large number of different animal and vegetable remains."

This has to be kept in mind when interpreting results obtained by various procedures.

The hydrogen peroxide method is believed to remove humus and colloidal matter but to have little effect upon undecomposed vegetable matter. This method is described in various textbooks but could not be applied successfully to the soils tested.

An increase instead of decrease in weight of the sample due to the H_2O_2 treatment has also been found in certain cases by Silfverberg (1957), who suggested that this phenomena might be caused by intermediate products during oxydation. Other investigators believe that the increase in weight results from the formation of Ca-oxalate (Dr. S. Pawluk*)

The total carbon content (TABLE X) includes organic and inorganic carbon (from carbonates) in the soil. The results of this determination shows that the carbon content tends to increase from the B- to C-horizon.

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* Personal communication

This suggests that the organic content is likely to be overshadowed by soluble salts and thus is not of great significance.

It must be mentioned that undecomposed roots have been removed prior to the test. It is felt that their presence might have an effect upon the soil structure but not on other properties.

At this point it is of interest to refer to some investigations concerning salt and organic matter in clays from the surroundings of Stockholm. Soederblom (1957) reports on the variation of shear strength, salt and carbon content in these clays from the surface to a depth of 15 to 25 meters. He came to the conclusion that the shear strength of these specific Swedish clays is not influenced so much by the salt content and that it seems as if the organic content is of greater importance.

Maclean and Sherwood (1961) studied the occurrence and effects of organic matter in relation to the stabilization of soils with cement. They were concerned with the top 50 to 60 inches of a soil profile and proposed to use pedological classification for estimating the depth of surface soil that contains active organic matter. It is felt that a similar investigation on Alberta soil series deserves consideration.

6:4 Analysis of Clay Minerals

6:4:1 X-Ray Analysis

Today X-ray diffraction is a standard method for identification of clay minerals. However, a quantitative analysis by means of X-rays is still a matter of controversy. In general, it is incorrect to assume that the diffracted X-ray intensity is a direct measure of the proportion of a component in a mixture (Brindley, see Brown, 1961). This fact has been

taken into account by Johns, Grim and Bradley (1954) by converting relative intensities to relative amounts on the basis of a very rough consideration of the intensities to be expected from a certain mineral type at different reflection angles. The method of analysis in use by the Research Council of Alberta and applied in this investigation relies on similar principles. Therefore the following comment by Brindley, in a book edited by Brown (1961) on the method proposed by Johns, Grim and Bradley is true also for the procedure used herein:

> "While this kind of analysis is exceedingly crude by comparison with other methods, it is reasonably sound in its approach, and for exceedingly poorly crystalline materials it is probably the best that can be devised."

Examination of TABLE XI shows, that the predominant clay mineral in Wetaskiwin and Navarre soils i montmorillonite, constituting 65 to 77% of the sum of kaolinite, illite and montmorillonite. B- and C-horizons of these soil profiles do not differ significantly in composition. However, according to these X-ray diffraction results, Camrose and Angus Ridge samples contained a considerably smaller percentage of montmorillonite in the upper horizon, with a corresponding increase in illite and kaolinite. This is probably due to lack of full expansion of montmorillonite in glycol due to adsorption of organic matter.

In general, it is felt that the clay mineral montmorillonite is of great significance for the soils tested, due to the relatively large amount present and due to its outstanding properties which will be discussed subsequently.

6:4:2 Total Exchange Capacity

The range of the cation exchange capacity of the three major clay minerals is given by Grim (1953) as:

Kaolinite 3 - 15,

Illite 10 - 40,

Montmorillonite 80 - 150 milliequivalents/100 grams.

Assuming that the percentage finer 0.002 mm comprises all clay minerals, it could be expected that a soil whose clay fraction is predominantly montmorillonite exhibits a higher exchange capacity than a soil with the same clay content, but mainly kaolinite. Using data from this investigation augmented by test results obtained by Hamilton* of the Alberta Research Council, FIG. 23 was plotted. Black points, representing soils with an estimated montmorillonite content of more than 70% should plot within the sector between line A and line B if the following conditions are fulfilled:

1. No other soil constituents contribute to the exchange capacity but montmorillonite, illite and kaolinite.
2. The total exchange capacity is directly related to the relative amounts and exchange capacities of the individual clay minerals.
3. The quantitative analysis of clay minerals by X-ray diffraction, as used to obtain these results, is correct.

Although the above assumptions are rather crude, the results seem quite reasonable: only 2 of 15 soils with more than 70% montmorillonite

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* Personal communication

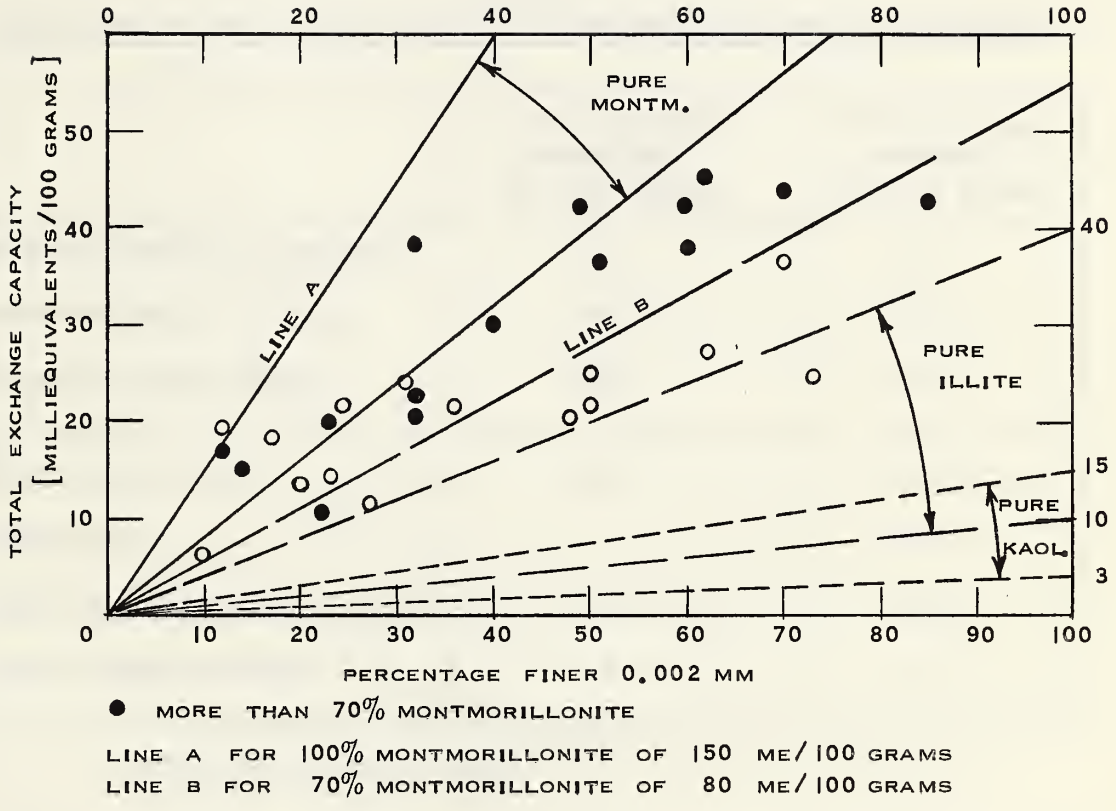

FIGURE 23. – RELATIONSHIP BETWEEN TOTAL EXCHANGE CAPACITY AND CLAY CONTENT [% FINER 0.002 MM].

do not fall within the predicted range.

In general, previous research dealt mainly with the effect of exchangeable cations on engineering soil properties and did not consider the anion exchange capacity of a clay. Values of cation and anion exchange capacities for various montmorillonites and kaolinites as reported by Weiss et al (1956) are given in TABLE XV.

TABLE XV

CATION AND ANION EXCHANGE CAPACITY OF MONTMORILLONITE AND KAOLINITE

	Cation exchange capacity me /100 grams	Anion exchange capacity me /100 grams
Montmorillonite Geisenheim	91	31
Montmorillonite Wyoming	99	23
Montmorillonite Cyprus	108	23
Kaolin Boluvit AG	10	20
Kaolin Milos	7	13
China Clay	4	12
Kaolin Schnaittenbach	2	6

(After Weiss et al, 1956)

From this table it is evident, that anion exchange is of much greater significance relative to cation exchange for kaolinite than for montmorillonite. Since a soils engineer in Alberta is more likely to be involved in problems associated with montmorillonitic clays, it seems justified that research of physico-chemical nature was concentrated on the

cation exchange complex, neglecting possible anionic phenomenas.

6:5 Osmotic Interpretation of Consolidation Test Results

For better understanding of this section, the reader is referred to Appendix D which explains the fundamentals of osmosis and outlines the theories of Ruiz (1962) and Bolt (1956) in more detail.

Bolt (1956) considered pure clays only; therefore his calculations which involve a computation of the distance between individual clay plates, are not readily applicable to soils as they usually occur in nature.

Ruiz (1962), applies the concept of osmosis without membrane to a salt free clay soil-water system at a moisture content between the liquid and plastic limits. He considers the following conditions:

1. The water occupying the free spaces between the solid particles acts as a dispersion medium (solvent) for the exchange cations.
2. The exchangeable cations tend to distribute themselves uniformly throughout the liquid, but are subjected to electrostatic attractive forces by negative charges on the surface of the solid particles. These forces play the role of the semipermeable membrane and cause an osmotic pressure to develop.
3. Considering plane particles it can be assumed that there is no change in concentration of the exchange cations with increasing distance up to a film thickness of the order of hundreds of molecules.

Using Van't Hoff's law, Ruiz arrives at the following expression

for the theoretical osmotic pressure:

$$(Po)\ ideal = R\ T\ \frac{"T"}{wVa},$$

where: R = universal gas constant

T = absolute temperature,

"T" = total exchange capacity,

w = moisture content, and

Va = average valence of exchangeable cations.

The real osmotic pressure (Po) real, as measured in the consolidation test, is expected to be smaller than (Po) ideal and Ruiz writes:

$$(Po)\ real = (Po)\ ideal \times f(w)$$

where f is a coefficient smaller than 1 and called activity factor, itself depending on the moisture content of the soil.

Knowing the characteristics of the exchange complex, it is possible to determine the variation of the activity factor f from consolidation test results. FIG. 24 gives the function f(w) for the three Alberta soil series tested in this investigation and for various homionic modifications of Edmonton clay, examined in previous research at the University of Alberta.

Results obtained from Locker's data (1963) illustrate how the activity factor decreases with increasing salt content. This is to be expected since Ruiz's formula was established for salt free soils.

One dimensional consolidation test carried out by Hamilton (1961) and triaxial consolidation tests by Thomson (1963) confirm that the type of adsorbed cation significantly affects the osmotic activity of a soil. In both cases it was found that the Na-ion plays an outstanding role in determining consolidation characteristics.

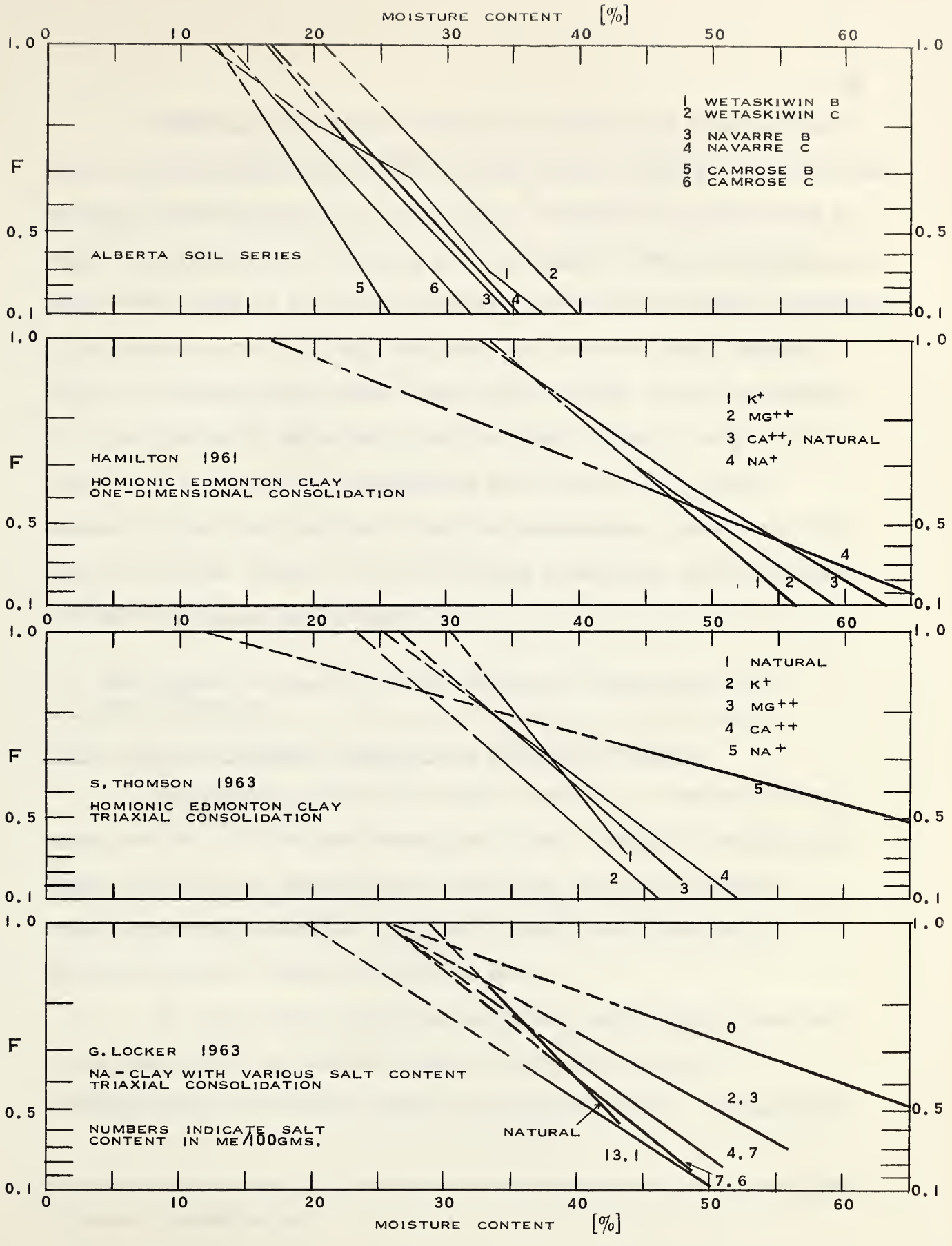

FIGURE 24. – OSMOTIC ACTIVITY F AS A FUNCTION OF THE MOISTURE CONTENT.

Examining the activity factors for some natural Alberta soils it seems that the osmotic activity at the same moisture content is lower in the B- than in the C-horizon of a soil profile. Therefore it is felt that for these soils the effects of soluble salts on osmotic forces are considerably smaller than those of the cation exchange complex and other basic properties. If the natural salts in a soil are present in only very small amounts, effects as observed from Locker's data would probably be more noticeable. It is the opinion of the writer, that the theory of Ruiz, owing to its simplicity, is valuable in interpreting consolidation test results. However for practical purposes it has its shortcomings, since it is found that not only the valence, but also the type of adsorbed cations affects the osmotic pressure significantly.

6:6 Some Aspects of Chemical and Mineralogical Interpretation of Soil Properties

6:6:1 The Total Exchange Capacity as a Basic Soil Property

Assuming that the total exchange capacity is a measure of the energy available for moisture adsorption, then a correlation should exist between the exchange capacity and the swelling, the plastic index or other engineering properties. This has already been pointed out by Wooltorton (1954) in regard to monionic soils.

To check these correlations on natural soils, results obtained by the author were supplemented by data from various sources: Winterkorn (1936), Wooltorton (1954) and Hamilton (1964)*. The majority

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* Personal communication

of the information used, originated from Hamilton's work.

FIG. 25 shows the relationship of liquid limit to total exchange capacity and to clay content. The two plots show, that in case of the liquid limit, the total exchange capacity does not offer a much better relationship than the clay content as determined by a standard engineering test.

Black points in FIG. 25 and 26 represent soils which are known to contain more than 10% Na-ions in the exchange complex. When comparing two soils with the same total exchange capacity, the writer expected the soil with the higher Na-content to exhibit a higher liquid limit. However, this effect cannot be observed in FIG. 25; probably due to the fact that the percentage Na^+ did not amount to more than 25% (average of Cam. B); further, it must be remembered that the samples are multionic.

Hamilton (1961) showed that the liquid limit of a certain Na-Ca-clay did not increase compared to a homionic Ca-clay when the percentage Na^+ was less than 50%.

The correlation between total exchange capacity and plasticity index is fairly good (FIG. 26). Considering that, it is not surprising that optimum moisture content and swelling potential are related to exchange capacity as well. A variation of the sodium content in a range below 25% does not seem to affect these properties significantly.

Winterkorn (1940) measured a considerably higher optimum moisture content for K-Putnam clay than for other homionic modifications. No effect of varying K^+-percentage was detected; however this is understandable, since potassium in most instances, constitutes only a very small

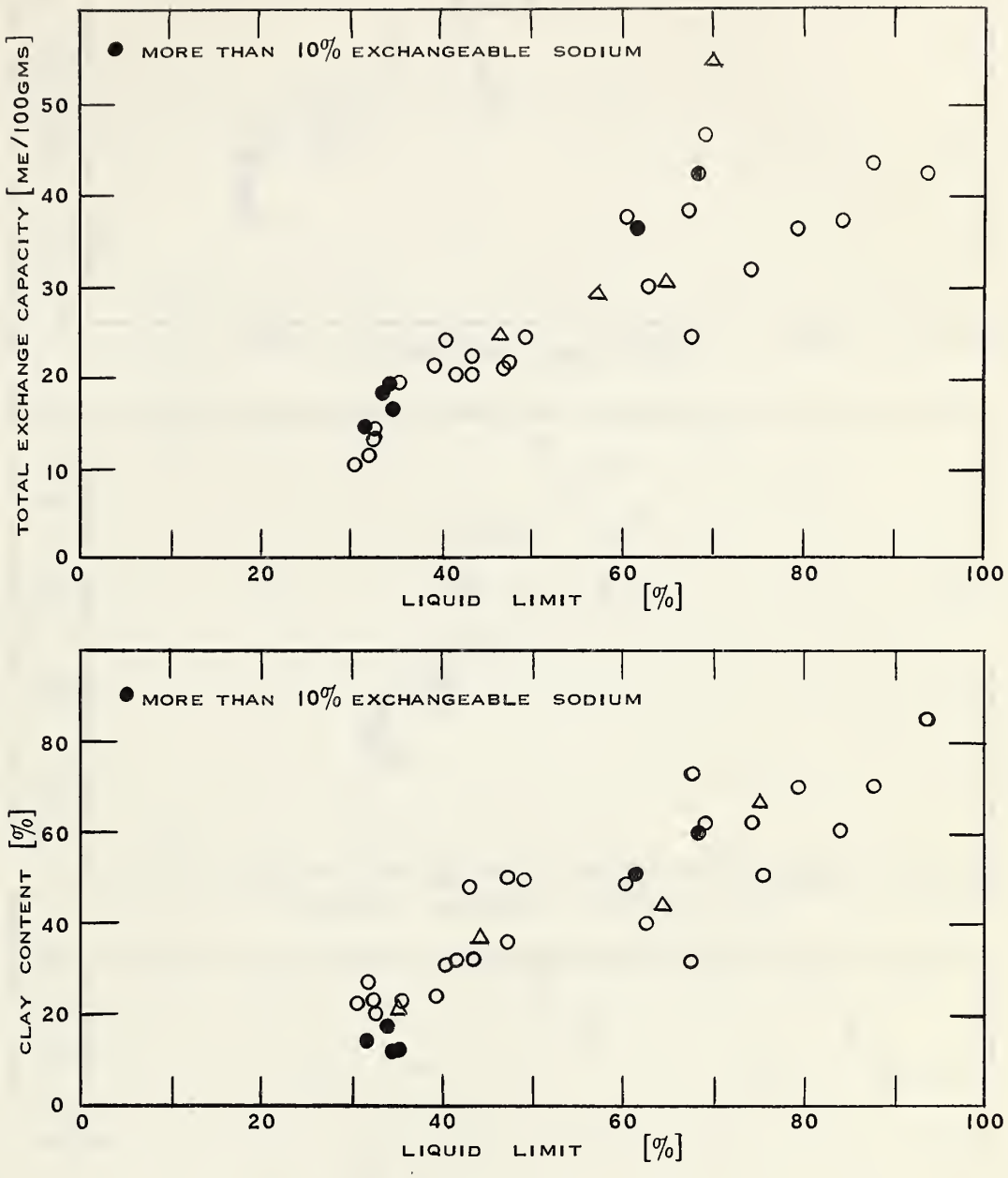

FIGURE 25. – RELATIONSHIP OF LIQUID LIMIT TO TOTAL EXCHANGE CAPACITY AND CLAY CONTENT [% FINER 0.002 MM].

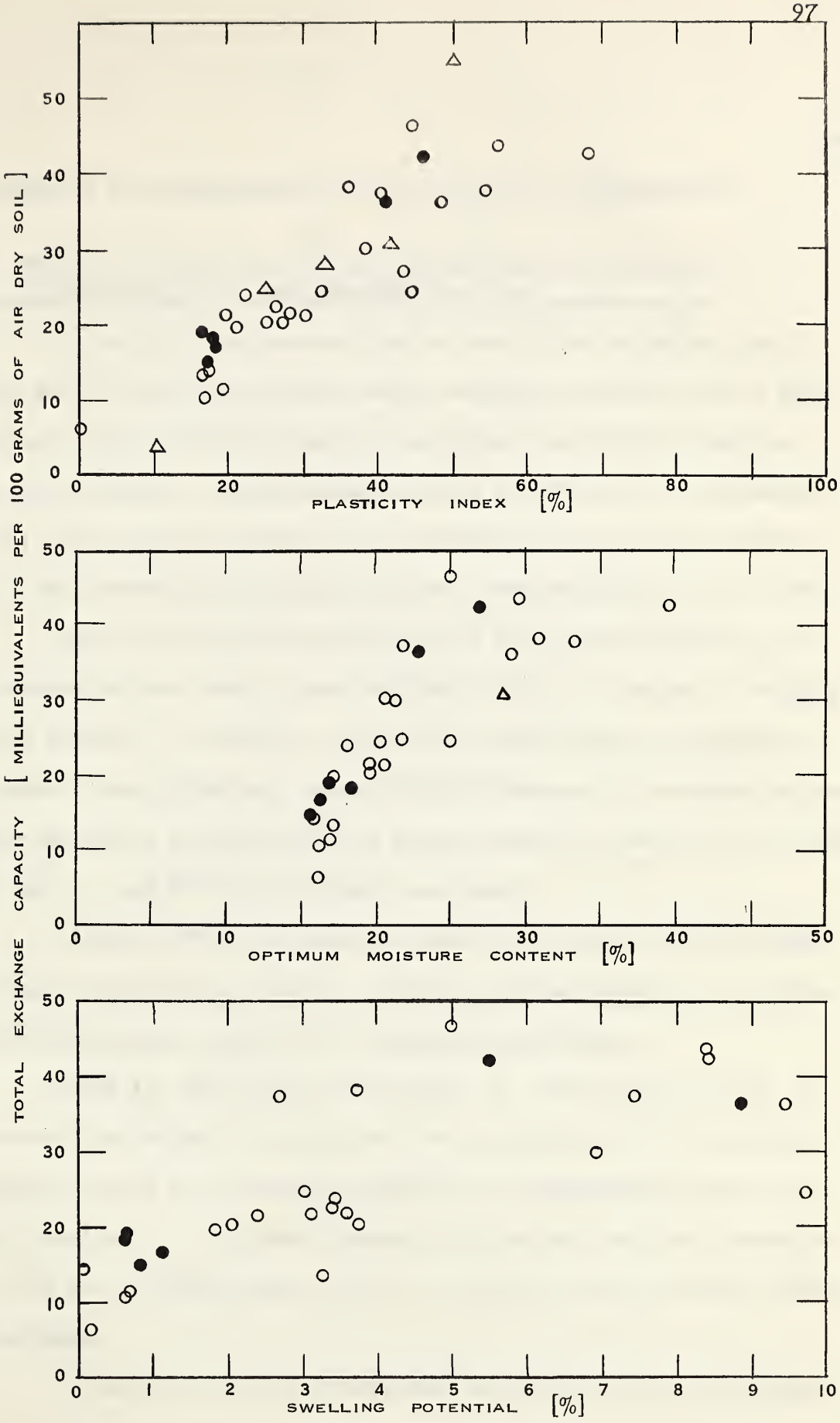
TOTAL EXCHANGE CAPACITY [MILLIEQUIVALENTS PER 100 GRAMS OF AIR DRY SOIL]
PLASTICITY INDEX [%]
OPTIMUM MOISTURE CONTENT [%]
SWELLING POTENTIAL [%]
SOURCE OF DATA: ● ○ AUTHOR AND HAMILTON, 1964
△ WOOLTERTON, 1954, AND WINTERKORN, 1936
● → SAMPLES WITH MORE THAN 10% EXCHANGEABLE SODIUM

FIGURE 26. – RELATIONSHIP OF TOTAL EXCHANGE CAPACITY TO PLASTICITY INDEX, OPTIMUM MOISTURE CONTENT AND SWELLING POTENTIAL.

percentage of the exchangeable cations in the soils investigated.

6:6:2 Effect of Various Cations and Electrolytes on Properties of Montmorillonite and Lake Edmonton Clay

It is felt that montmorillonite, due to its expanding type of lattice and its high moisture and cation adsorption capacity, has a more pronounced effect on soil properties than other clay minerals such as illite and kaolinite. Since montmorillonite is present to a considerable degree in many soils in Alberta, its characteristics may help to explain some of the properties of natural clay soil mixtures found in this area.

Kazda (1961) has shown by means of X-ray investigations, how the distance between basal planes (defined in FIG. 27) changes at varying moisture contents. As shown in FIG. 28 this relationship is different for various types of homionic montmorillonite because the adsorbed cations between the sheets are hydrated with unequal amounts of water, or, in other words, Na^{+}, K^{+} and Ca^{++} have unequal ionic radii.

Hofmann (1956), as quoted in TABLE XVI, reports on the changes of distance between basal planes of homionic montmorillonite in a corresponding electrolytic solution with varying concentration.

TABLE XVI shows that the distance d between basal planes of Ca-montmorillonite hardly changes when the concentration of the solution is reduced from 2N to 0 (distilled water). For Na-montmorillonite in a Na-salt solution, d increases suddenly at a certain very low concentration. The use of NaOH instead of NaCl in solution does not seem to affect this phenomena.

It was felt that the fundamental strength properties of montmor-

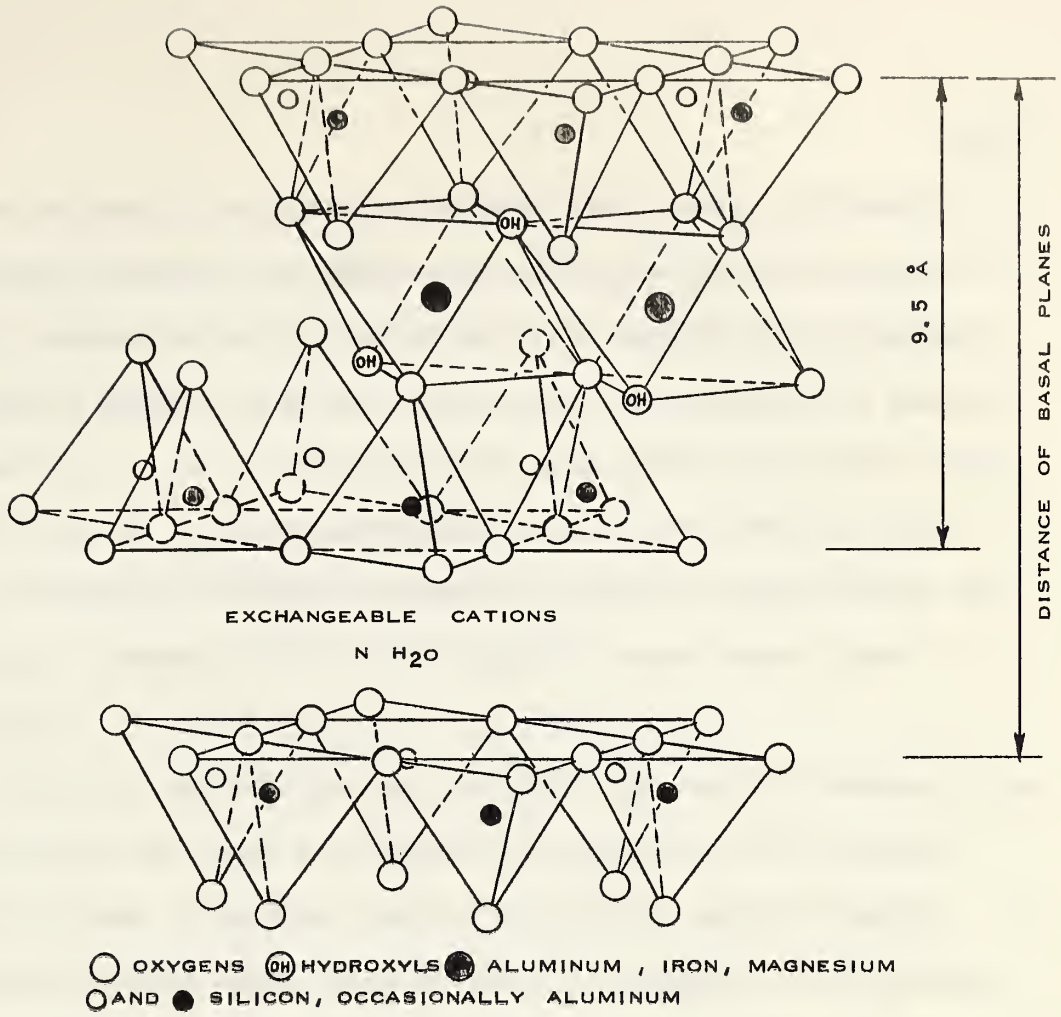

FIGURE 27 . – DIAGRAMMATIC SKETCH OF THE STRUCTURE OF MONTMORILLONITE [AFTER GRIM, 1953].

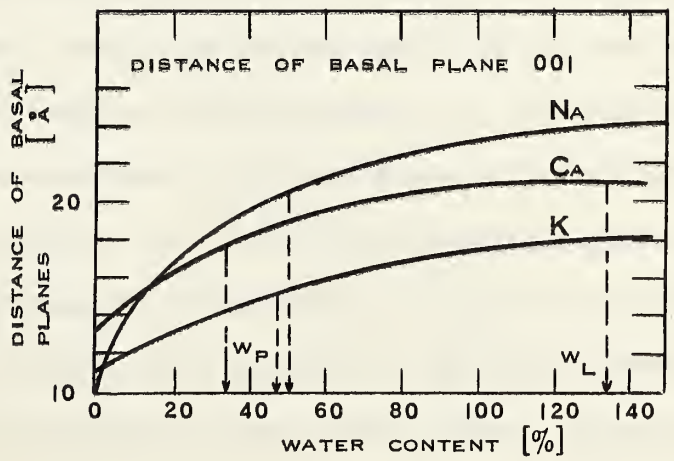

FIGURE 28 . – DISTANCE OF BASAL PLANES OF N_A , K , AND C_A - MONTMORILLONITE UNDER VARIOUS MOISTURE CONDITIONS [AFTER KAZDA , 1961].

illonite are related to the distance between basal planes. No results of strength tests on homionic pure montmorillonite were readily available to the writer; however extensive studies have been carried out on homionic modifications of Edmonton clay with various salt concentration in the pore water. Edmonton clay as investigated by Thomson (1963) and Locker (1963) contains at least 30 to 40% montmorillonite in its clay fraction (finer 0.002 mm). Therefore an attempt was made to correlate quantitatively the friction angle of Edmonton clay to the distance between basal planes of montmorillonite.

In FIG. 29 the friction angle of salt free homionic Edmonton clay, as determined from the results of Thomson, is compared to the distance d as reported by Kazda for montmorillonite with various adsorbed cations. It shows that the friction angle increases when d decreases. The distance d was taken at an arbitrary moisture content of 40%; however the same qualitative comparisons could be made over the whole plastic range of the specific montmorillonite investigated by Kazda (approximately 34 to 134%).

FIG. 30 correlates values reported by Hofmann(see TABLE XVI) with strength parameters determined by Locker for the Na-modification of Edmonton clay with various Na^+-concentration in the pore water.

Locker observed a rapid change in $\emptyset'$ at a certain relatively low critical salt concentration, after which the friction angle seems to remain approximately constant. It is felt to be more than a pure coincidence that, when decreasing the concentration of salts in Na-montmorillonite to about the same critical value between 0.2 and 0.4N, Hofmann noticed a sudden increase in distance between basal planes. Furthermore, Locker's

results do not show any appreciable change in Ø' of a Ca-modification of the same soil with a various content of free calcium ions in the pore water; this is in accordance with a practically constant distance d of Ca-montmorillonite in a $CaCl_2$-solution, as shown in TABLE XVI.

TABLE XVI

DISTANCE BETWEEN BASAL PLANES OF MONTMORILLONITE (GEISENHEIM)

(after Hofmann, 1956)

Concentration of solution N	$CaCl_2$- solution Ca-montm. Å	NaCl-solution Na-montm. Å	NaOH-solution Na-montm. Å
2.0	19.2	16.6	16.7
1.0	19.3	19.2	19.1
0.5	19.4	19.6	19.6
0.4	-	19.8	20.0
0.3	-	∞	∞
0.2	19.5	∞	∞
0.02	19.8	∞	-
0.002	20.0	∞	-
dist. H_2O	20.0	∞	∞

Note: ∞ indicates that distance exceeds 150 Å (upper limit of distances measurable by X-ray diffraction techniques).

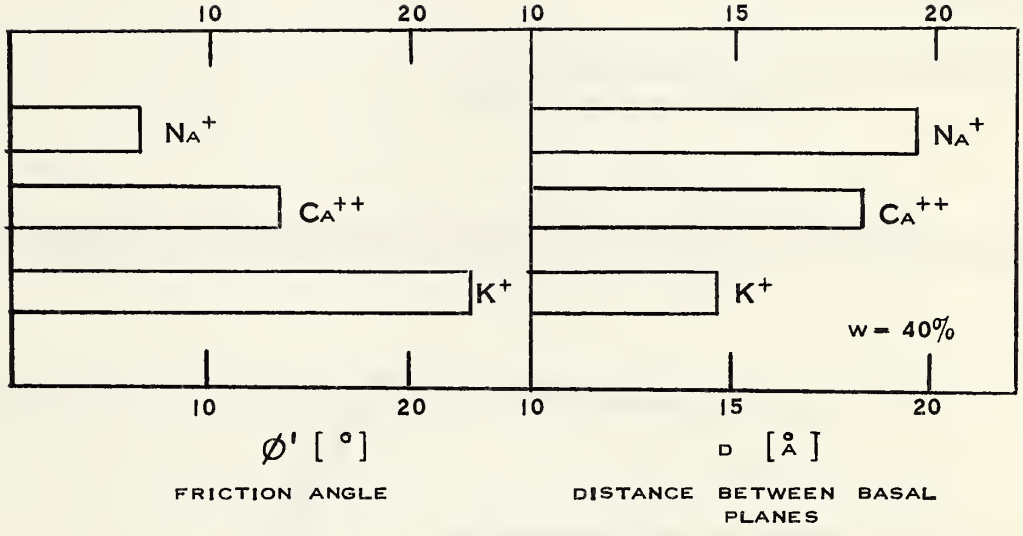

FIGURE 29 . – FRICTION ANGLE OF SALT FREE HOMIONIC MODIFICATIONS OF EDMONTON CLAY AND DISTANCE BETWEEN BASAL PLANES OF MONTMORILLONITE MODIFICATIONS [AFTER S. THOMSON, 1963, AND KAZDA, 1961] .

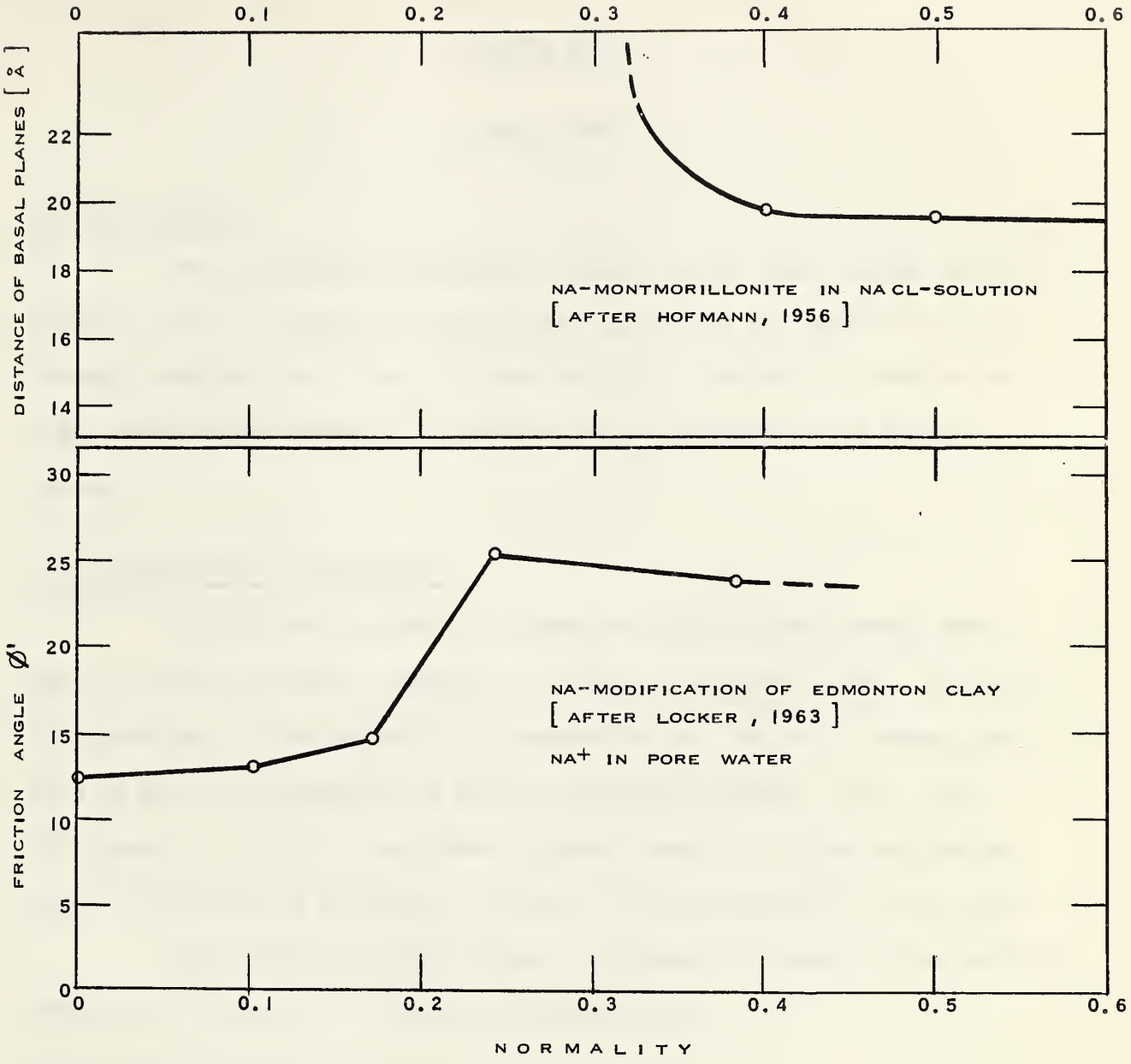
DISTANCE OF BASAL PLANES [Å]
NA-MONTMORILLONITE IN NACL-SOLUTION
[AFTER HOFMANN, 1956]
FRICTION ANGLE Ø'
NA-MODIFICATION OF EDMONTON CLAY
[AFTER LOCKER, 1963]
NA+ IN PORE WATER
NORMALITY

FIGURE 30. – RELATION OF FRICTION ANGLE OF NA-CLAY AND DISTANCE BETWEEN BASAL PLANES OF MONTMORILLONITE TO ELECTROLYTE CONCENTRATION.

CHAPTER VII

CONCLUSIONS

7:1 Soil Types

The predominant exchangeable cation of all soils tested in this project is Ca^{++}. However, assuming that 15 or more per cent Na^{+} in the exchange complex give a soil Na-characteristics, Wetaskiwin, Camrose and Angus Ridge may be referred to as Na-soils, while Navarre and Malmo are Ca-soils.

7:2 Engineering Classification

Liquid limit, plasticity index and plastic limit change from the B- to the C-horizon. However, no definite trend was found. The flow index and tan B value seemed to be associated with the salt content, but this is not fully supported by previous tests on homionic soils. The shrinkage limit shows a consistent increase from B- to C-horizon, which might illustrate the different structure of these materials in the field.

The presence of salts seems to increase the value of the specific gravity as observed in B- and C-horizon material.

7:3 Compaction and Strength

Results of this investigation show that the optimum moisture content may vary up to 4%, the maximum density up to 4.8 lbs/ft^3 depending whether the compaction test is run on material from the B- or C-horizon

Swelling characteristics of B- and C-horizon also show considerable difference, but without any trend.

Unconfined compression tests indicated that there might be a considerable difference in strength of B- and C-material at the same moisture content. The log strength-moisture content curves of soil from B- and C-horizon might be approximated by two parallel straight lines in the range above optimum moisture content. There is no strong indication that the slope of this line is affected by soluble salts.

7:4 Consolidation and Swelling

The salt content does not seem to be the main factor in determining volume change characteristics as measured in a consolidation test on remoulded soil.

Swelling tests on compacted soils indicate that Wkn. soil (Na-soil) has higher swelling characteristics than the Nv. soil (Ca-soil), which shows otherwise very similar properties. No effects of soluble salts are apparent. The value of the swelling potential cannot be evaluated as a basic soil property since it represents a volume change under very special conditions. Therefore physico-chemical interpretation of these results is not fully justified.

7:5 Clay Content

The determination of the clay content by menas of a sedimentation test is found to be very sensitive to pre-treatment and type of dispersing agent used. Tests showed that natural soluble salts affect strongly the flocculation characteristics of a soil suspension and therefore it can be

expected that the grain size analysis of fine-grained soils is influenced by the presence of salts in these soils.

7:6 Soluble Salts

The amount of soluble salts cannot be evaluated reliably from the analysis of the exchange complex of a natural soil. The determination of soluble salts by weight is very sensitive to procedural errors. It is felt that the electrical conductivity of a solution gives a fairly good indication of the soluble salts present, although the exact amount of salts by weight cannot be determined with this method, when the type of salt is not known.

The effect of salts on the behaviour of a soil will depend on their concentration in the pore water, their solubility and type.

The standard engineering tests are affected by soluble salts to a various degree, depending on the soil-water ratio used. There is a definite increase in salts from the B- to the C-horizon, more pronounced in a solonetzic than a chernozemic soil.

7:7 Organic Matter

Standard tests for determining the amount of organic matter in a soil do not differentiate between types of organic material present. Since the effects of organic matter on engineering properties might vary with the chemical composition, any value of "organic content" is questionable. The total carbon content, as determined in this test series includes inorganic and organic carbon. Since the quantities found in B- and C-horizon are relatively small, it is felt that organic matter does not

influence engineering properties significantly in the soils tested.

An attempt to measure organic matter by means of the hydrogen peroxide method was not successful.

7:8 Theory of Osmosis as Applied to Soils

The osmotic theory as applied to soils by Ruiz is, owing to its simplicity, valuable in interpreting consolidation test results. However, for practical purposes it has its shortcomings, since it is found that not only the valence, but also the type of adsorbed cation affect the osmotic pressure significantly.

7:9 Mineralogical Analysis

A quantitative analysis of clay minerals by X-ray diffraction methods is not exact. However, test results indicate that montmorillonite is the predominant clay mineral in most soils considered in this investigation.

7:10 Total Exchange Capacity

The total exchange capacity is found to be intimately related to many engineering properties of a soil, as e.g. liquid limit, plasticity index, optimum moisture content and swelling.

Montmorillonitic clay minerals were found to contribute significantly to the total exchange capacity of several natural soils as found in Alberta.

7:11 Strength Characteristics of Homionic Clays

In a re-evaluation of results from previous research at the

University of Alberta, mineralogical data on montmorillonite were compared to strength parameters of Edmonton clay, whose fraction finer than 0.002 mm is believed to consist of at least 30 to 40% montmorillonite. It was found that there seems to be a fundamental relationship between the distance between basal planes of montmorillonite, a mineral of the expanding lattice type, and the friction angle of montmorillonitic clays.

CHAPTER VIII

RECOMMENDATIONS

8:1 Since many areas of Alberta are covered with saline soils, it is felt that the effect of salts on engineering properties deserves further attention.

Salts may occur in a soil in crystalline form or dissolved in the pore water. A particular soil property might be affected by dissolved salts only. The effective salt content, in this case, is lower than the total salt content, if only part of the salts present in the soil are dissolved. If it is assumed that all salts are in solution, their concentration in the pore water will change with moisture content. Any effects of dissolved salts will likely be directly dependent on their concentration, which can be expressed in moles per liter of solution, and not salt content, measured e.g., in grams of salt per 100 grams of soil solids.

In this light, it is felt that further investigations on saline soils should be based on the development of a reliable method of determining the effective salt content in a soil in regard to various properties.

It is recommended that a study be undertaken to determine how natural soluble salts affect the results of such standard engineering tests as the determination of moisture content, Atterberg limits, specific gravity and grain size distribution.

8:2 Research carried out by Maclean and Sherwood (1961), among others indicates that soil from various horizons in a single soil profile may react differently on Portland Cement stabilization. This finding stimulates the interest of the engineer in soil science and pedological data compiled by soil survey organizations. It is felt that valuable research could be carried out in examining consolidation, swelling and strength properties of various saline and non-saline soils before and after treatment with different stabilizing agents, considering possible changes in characteristics from B- to C-horizon in a particular soil profile.

8:3 It seems to the writer that clay minerals of the expanding lattice type, such as montmorillonite are most significant in regard to any engineering soil properties. Research in the field of engineering clay mineralogy may give most significant information when concerned with the following problems:

a. Development of a quantitative analysis of clay mixtures, which is suitable for engineering purposes.

b. Determination of strength properties of pure montmorillonite, as related to the distance between basal planes, which varies with the type of adsorbed cation and the moisture content.

c. Tests on controlled mixtures of sand, silt and pure clay minerals to investigate the role of clay minerals in regard to engineering properties of a soil.

This work would require a knowledge of other fields of science

not commonly associated with Civil Engineering such as clay mineralogy and X-ray diffraction techniques.

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APPENDIX A

GRAIN SIZE DISTRIBUTION

- Hydrometer Analysis

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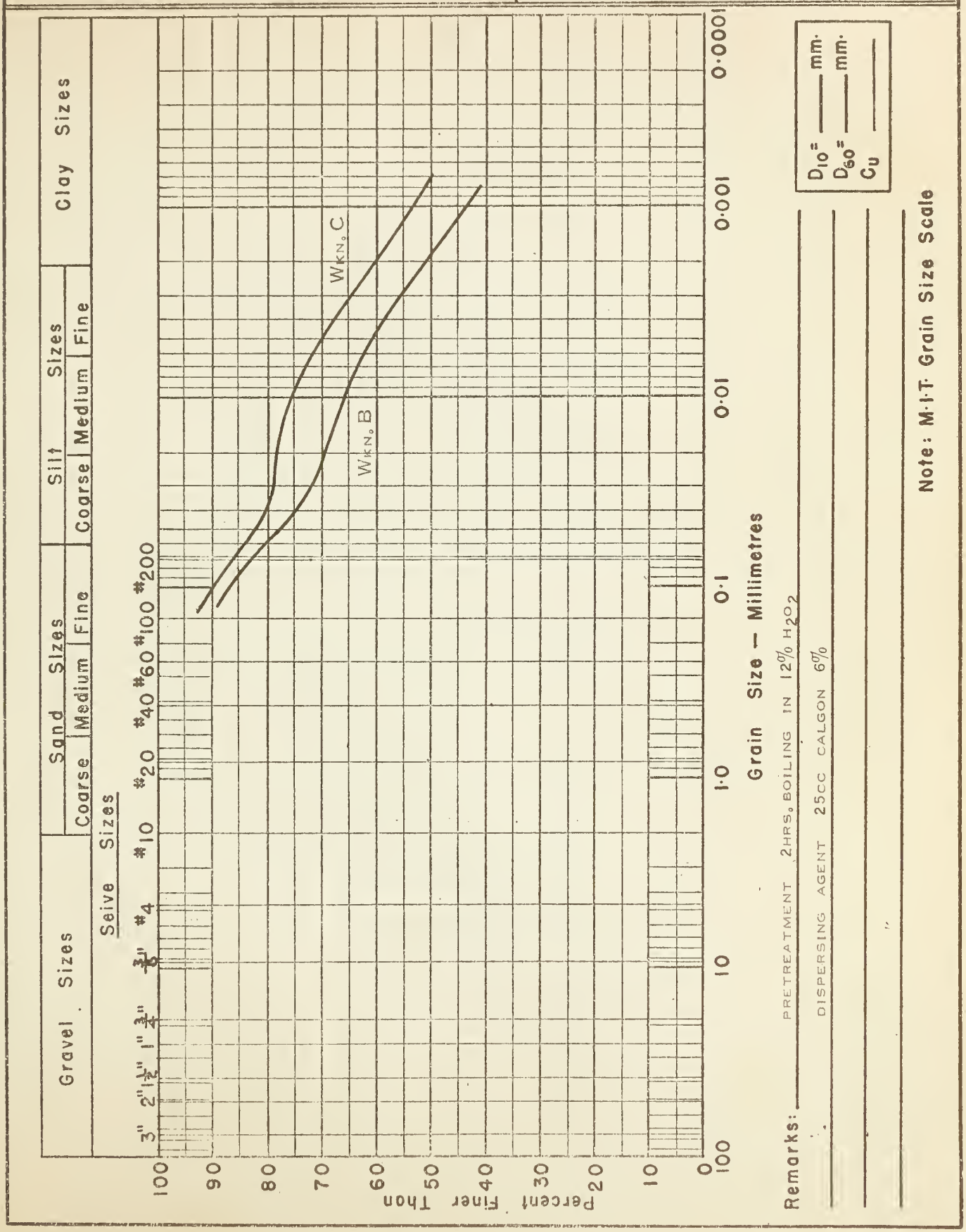
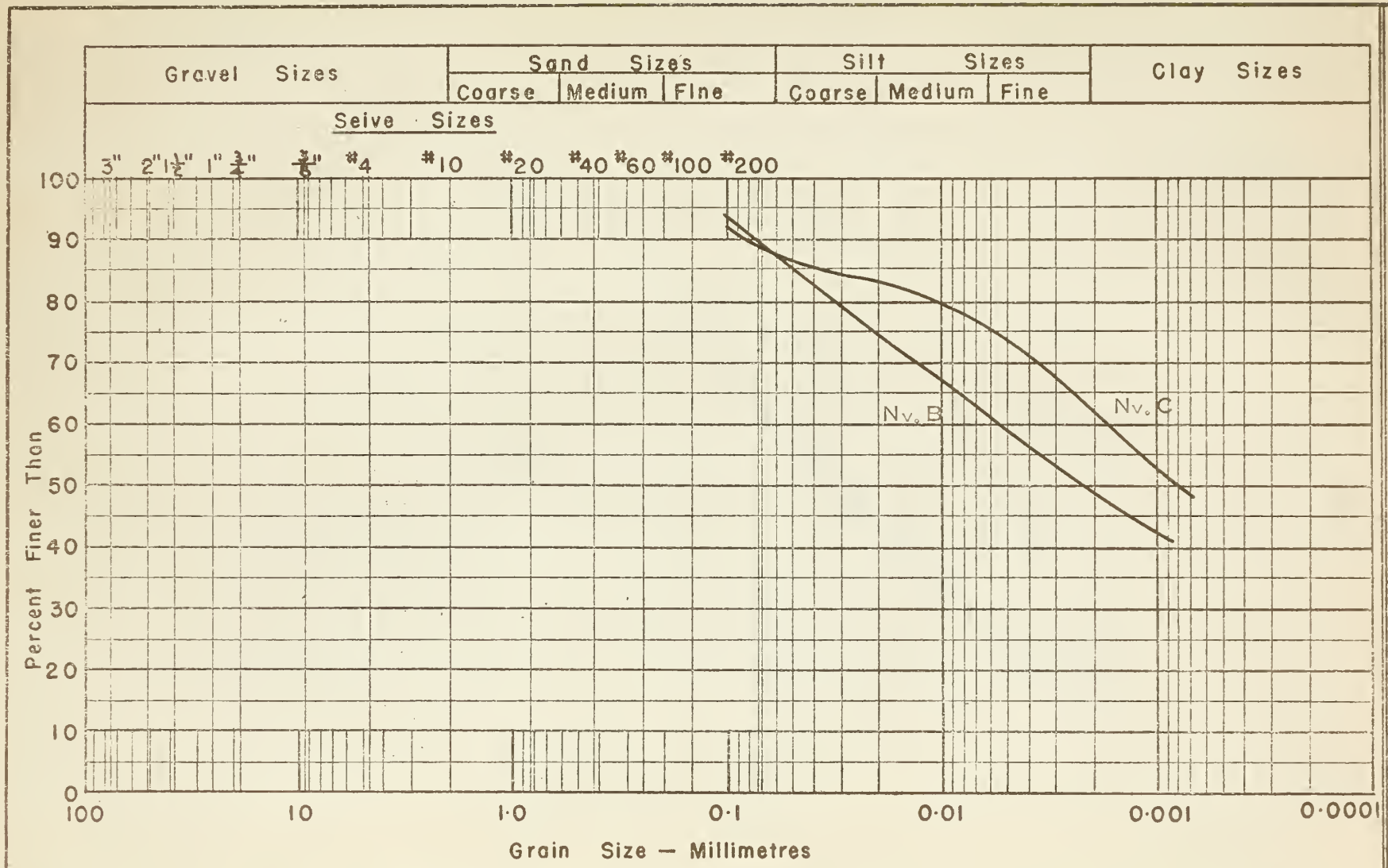
GRAIN SIZE CURVE

PROJECT	THESIS
SITE	
SAMPLE	WETASKIWIN B- AND C-HORIZON
LOCATION	
HOLE	DEPTH
TECHNICIAN	HAUSMANN DATE 1963





Remarks: PRETREATMENT 2HRS. BOILING IN 6% H_2O_2

DISPERSING AGENT 10CC CALGON 6%

D_{10} = ____ mm.

D_{60} = ____ mm.

C_u ____

Note: M.I.T. Grain Size Scale

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GRAIN SIZE CURVE

PROJECT THESIS

SITE

SAMPLE NAVARRE, B- AND C-HORIZON

LOCATION

HOLE DEPTH

TECHNICIAN HAUSMANN DATE 1963

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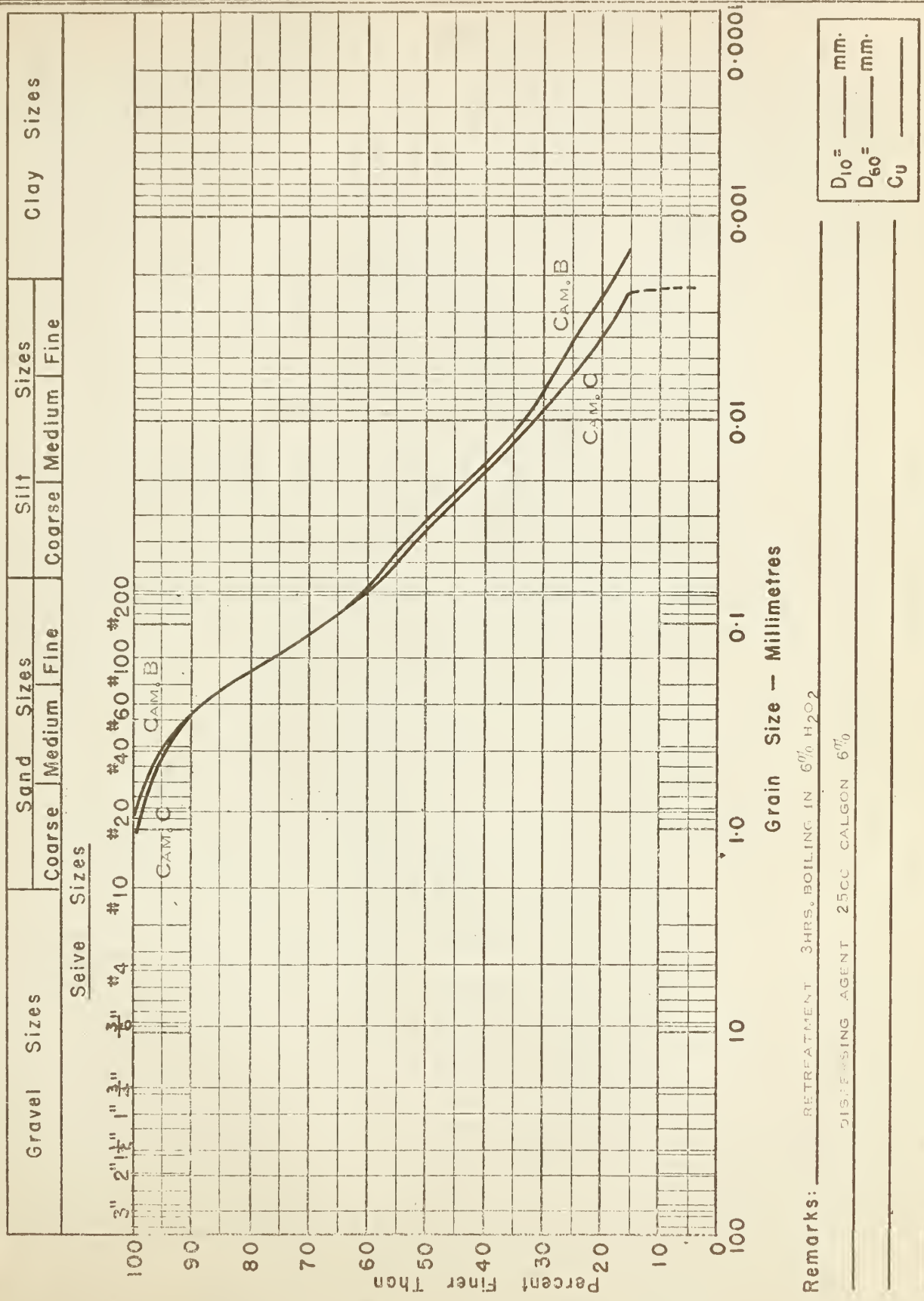
GRAIN SIZE CURVE

PROJECT	THESIS
SITE	
SAMPLE	CAMROSE B- AND C-HORIZON
LOCATION	
HOLE	DEPTH
TECHNICIAN HAUSMANN	DATE 1963



Remarks: RETREATMENT 3HRS. BOILING IN 6% H_2O_2

DISPERSING AGENT 25cc CALGON 6%

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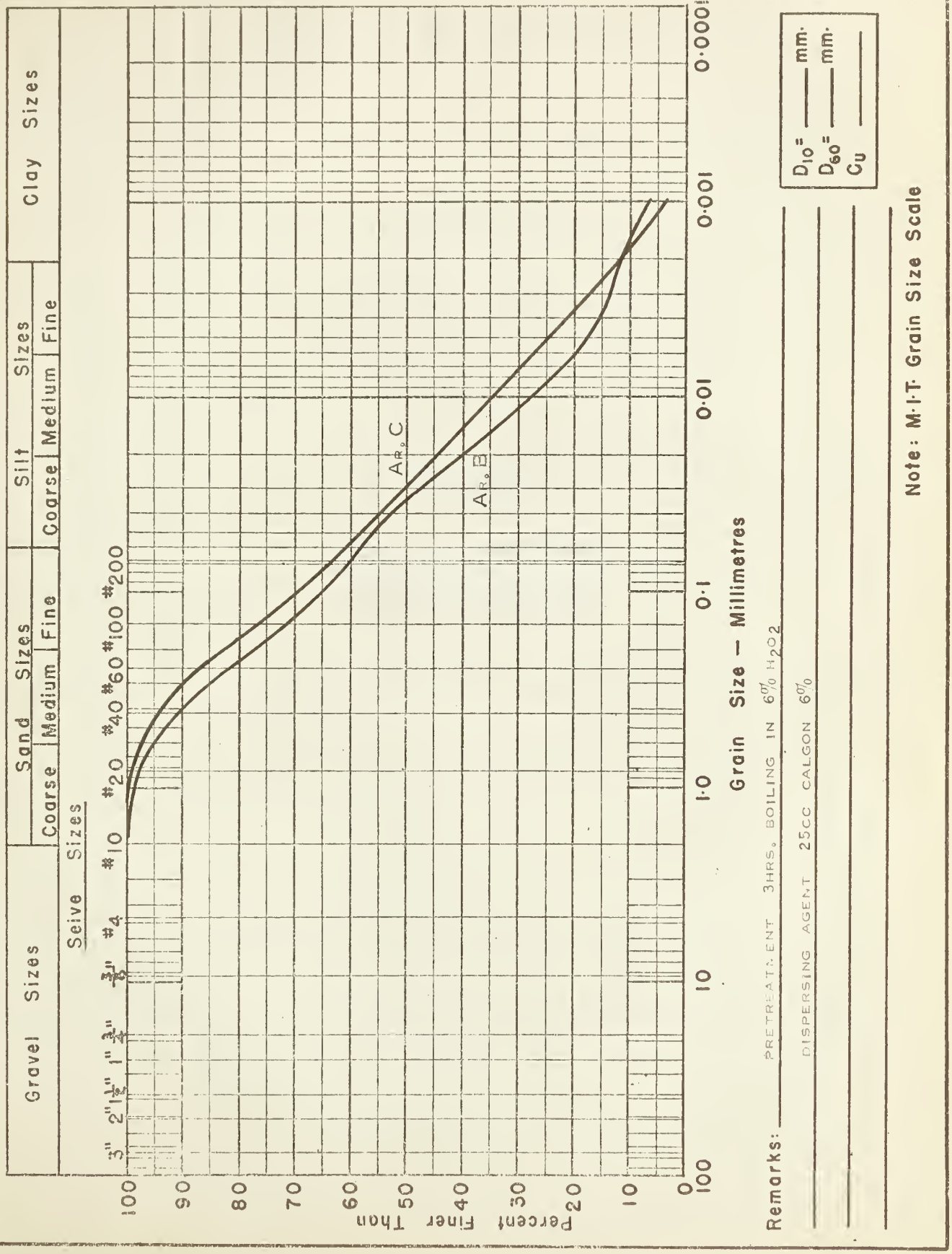
GRAIN SIZE CURVE

PROJECT THESIS
SITE
SAMPLE ANGUS RIDGE B- AND C-HORIZON
LOCATION
HOLE DEPTH
TECHNICIAN HAUSMANN DATE 1963



Remarks: PRETREATMENT 3HRS. BOILING IN 6% H_2O_2

DISPERSING AGENT 25CC CALGON 6%

APPENDIX B

SWELLING POTENTIAL AND PENETRATION RESISTANCE

SWELLING POTENTIAL AND PENETRATION RESISTANCE TEST RESULTS

SOIL TYPE	SP %	as compacted W %	as compacted PR kg/cm^2	after swelling W %	after swelling PR kg/cm^2
Wetaskiwin B	9.17	21.25	+4.5	33.7	.79
	5.30	24.75	2.69	33.1	.89
	3.65	27.4	1.72	31.6	1.08
	1.66	34.4	.72	36.9	.71
	9.82	19.4	+4.5	43.1	.45
	9.66	15.3	+4.5	43.5	.50
Wetaskiwin C	9.09	23	4.0	38	.59
	5.55	27.4	2.54	32.9	1.04
	3.88	30	1.65	35.6	.89
	2.48	32.9	1.09	37.0	.875
	1.08	35.2	.69	38.4	.695

SOIL TYPE	SP %	as compacted W %	as compacted PR kg/cm^2	after swelling W %	after swelling PR kg/cm^2
Navarre B	5.0	14.8	+4.5	39.3	.26
	3.48	19.5	+4.5	38.6	.37
	2.91	23.5	3.10	29.0	1.38
	1.09	27.4	1.81	29.6	1.41
	0.93	31.0	1.00	31.7	1.05
Navarre C	6.7	17.6	+4.5	40.6	0.31
	6.08	22.4	4.32	35.6	.78
	4.13	27.1	2.39	32.7	1.16
	2.55	29.9	1.66	32.8	1.18
	1.82	31.9	1.27	34.4	1.13

SWELLING POTENTIAL AND PENETRATION RESISTANCE TEST RESULTS

SOIL TYPE	SP %	as compacted W %	as compacted PR kg/cm^2	after swelling W %	after swelling PR kg/cm^2
Camrose B	3.33	12.3	+4.5	21.0	.95
	1.57	14.2	+4.5	21.5	1.00
	.68	16.3	2.72	20.5	1.49
	.61	18.3	1.66	19.4	1.37
	.42	20.2	.91	20.6	1.07
Camrose C	2.01	11.3	+4.5	22.3	.57
	1.47	13.4	+4.5	20.2	.93
	.90	15.2	3.25	17.6	1.70
	.77	17.0	1.72	18.3	1.41
	.19	19.4	.81	19.5	.93

SOIL TYPE	SP %	as compacted W %	as compacted PR kg/cm^2	after swelling W %	after swelling PR kg/cm^2
Angus Ridge B	1.00	14.8	4.42	21.20	1.56
	.85	16.72	3.32	18.95	1.98
	.39	18.75	1.70	20.70	1.71
	-.03	20.7	.96	21.05	1.17
	-.23	22.85	.63	22.95	.81
Angus Ridge C	1.79	13.75	+4.5	26.0	.47
	1.51	15.5	+4.5	20.9	1.53
	.69	17.65	2.25	20.2	1.63
	.19	19.55	1.27	20.7	1.19
	-.02	21.9	.66	22.1	.85

APPENDIX C

UNCONFINED COMPRESSION TEST

UNCONFINED COMPRESSION TESTS

SOIL TYPE	Unit Strain %	Vertical Stress psi	Moisture Content %	Density lbs./cu.ft.	Saturation
Wkn. B	18.7	26.4	26	95.0	91.4
	14.3	37.6	23.4	96.7	84.7
	16.2	41.2	23.0	97.1	84.1
	10.6	56.5	20.6	95.3	72.1
	12.5	53.0	20.6	97.5	76.2
	5.4	44.5	18.5	85.0	50.7
	3.6	39.9	18.5	85.6	51.4
	2.5	35.9	14.4	82.5	37.2
	2.1	36.8	14.2	82.5	36.7
	2.9	38.9	14.6	82.2	37.5
Wkn. C	13.6	20.5	28.6	91.3	91.2
	8.0	16.7	28.5	91.5	91.0
	14.5	39.2	24.9	94.8	86.3
	7.8	31.5	25.1	94.0	85.1
	8.5	41.8	21.8	90.8	68.7
	14.0	45.5	21.8	90.2	67.5
	14.6	14.0	31.7	87.0	91.2
	16.2	13.3	31.6	87.0	90.8

UNCONFINED COMPRESSION TESTS

SOIL TYPE	Unit Strain %	Vertical Stress psi	Moisture Content %	Density lbs./cu.ft.	Saturation %
Nv. B	1.97	35.1	14.1	85.0	38.8
	2.72	37.2	14.0	86.7	40.1
	2.71	32.9	14.1	85.8	39.6
	6.19	38.7	18.7	91.8	60.5
	6.11	38.7	18.6	91.2	59.5
	5.95	44.4	18.5	92.4	60.7
	7.20	38.3	18.5	92.0	59.5
	15.3	37.2	22.0	96.2	79.2
	16.2	35.1	22.2	96.1	79.8
	19.8	33.6	22.5	96.5	82.0
	19.1	21.2	25.7	95.1	90.4
	20.1	20.4	25.8	94.6	89.2
	21.1	21.3	25.8	95.0	90.4
	19.9	13.4	29.0	90.2	90.5
	21.1	13.5	29.1	89.9	90.2
	20.0	12.6	29.2	88.3	87.1
	19.6	12.8	29.1	88.9	85.0
Nv. C	2.78	31.3	16.69	85.4	46.1
	3.11	33.0	16.65	85.1	45.7
	2.74	37.7	16.69	86.5	47.2
	2.77	38.1	16.59	86.5	47.0
	11.92	42.5	22.0	94.1	74.8
	13.1	43.8	21.9	93.0	72.4
	12.3	44.0	22.0	95.0	76.2
	13.1	38.4	22.1	92.0	71.4
	19.35	29.5	25.8	94.9	89.1
	19.5	29.5	25.8	94.4	89.3
	19.7	27.1	26.0	94.5	89.0
	21.0	18.25	28.8	91.0	90.7
	21.0	18.1	28.6	89.7	87.4
	19.7	17.5	28.7	90.4	89.0
	22.6	15.35	30.5	88.5	90.5
	22.1	13.85	30.7	87.3	88.7
	23.2	14.60	30.6	87.8	89.5

UNCONFINED COMPRESSION TESTS

SOIL TYPE	Unit Strain %	Vertical Stress psi	Moisture Content %	Density lbs./cu.ft.	Saturation %
Cam. B	3.85	30.6	11.84	102.8	50.0
	4.78	31.4	11.61	101.5	47.5
	4.21	31.4	11.59	101.0	46.8
	9.06	30.4	13.79	105.1	62.0
	8.22	20.0	13.9	101.7	57.3
	8.35	28.5	13.75	104.9	61.1
	22.3	26.3	16.0	109.9	81.0
	17.3	23.8	16.0	108.6	78.6
	19.3	24.1	16.0	109.9	81.0
	28.1	16.1	18.0	107.2	85.2
	27.1	16.8	18.04	108.9	89.0
	28.3	13.25	19.1	105.9	86.0
	31.0	12.9	19.0	105.5	85.9
Cam. C	4.24	29.8	10.48	101.0	42.4
	2.98	31.1	10.52	101.0	42.6
	3.51	32.7	10.55	102.5	44.4
	7.45	30.2	13.00	108.0	62.6
	6.82	29.3	13.0	107.0	61.2
	7.04	26.6	13.06	105.7	59.5
	14.4	32.8	14.58	112.2	78.7
	13.4	29.3	14.6	112.0	78.5
	12.4	30.1	14.59	110.4	75.0
	24.7	20.4	16.52	112.8	90.8
	23.8	21.4	16.15	111.8	85.8
	29.8	11.5	18.62	108.2	90.5
	30.3	11.6	18.6	106.9	87.1

UNCONFINED COMPRESSION TESTS

SOIL TYPE	Unit Strain %	Vertical Stress psi	Moisture Content %	Density lbs./cu.ft.	Saturation %
Ar. B	7.37	31.3	14.1	103.1	60.4
	5.65	27.4	14.05	104.9	63.0
	6.1	30.7	14.20	104.5	62.4
	13.9	28.2	16.09	107.4	77.0
	15.1	28.6	16.14	109.0	80.4
	13.2	27.4	16.0	108.1	78.0
	32.6	19.2	18.12	108.0	88.1
	27.8	19.0	18.15	107.0	85.8
	27.1	19.2	18.13	108.0	88.1
	28.8	9.7	20.06	103.9	87.7
	29.0	10.3	19.82	103.1	85.0
	22.4	6.2	21.85	100.2	87.1
	27.1	6.2	21.65	99.0	83.8
Ar. C	4.75	35.2	13.32	102.9	56.2
	3.76	32.4	13.08	102.1	53.9
	3.98	27.4	13.74	101.4	55.5
	8.1	33.5	15.0	107.5	71.0
	8.5	30.1	15.07	105.8	68.0
	8.9	35.9	15.19	108.2	73.2
	18.6	29.2	16.89	111.5	88.5
	25.0	29.6	16.69	112.1	88.6
	22.2	30.3	16.60		
	27.3	19.5	18.85	106.6	86.8
	25.6	22.1	18.80	107.4	88.8
	29.8	8.5	20.85	102.0	85.7
	32.5	9.1	20.85	103.1	88.2

APPENDIX D

NOTES ON THEORY OF OSMOSIS AS APPLIED TO SOILS

1. The phenomenon of osmosis.
2. Theory of Ruiz.
3. Theory of Bolt.

1. The Phenomenon of Osmosis

a. Osmotic Pressure

If two solutions of different concentration, or solution and solvent, are separated by a membrane permeable to solvent (dispersing medium, e.g. water) but impermeable to solute (dissolved material, e.g. Na^+-ions), the solvent will diffuse into the more concentrated solution (Daniels and Alberty, 1955, p. 223). This differential flow process that distinguishes between solvent and solution is called osmosis.

The osmotic pressure is defined as that hydrostatic pressure which must be applied to a solution in order just to prevent the flow of solvent through the semipermeable membrane to the more concentrated solution.

The osmotic pressure is commonly measured in instruments called osmometers. The basic principle applied in these measurements is illustrated in FIG. 1.

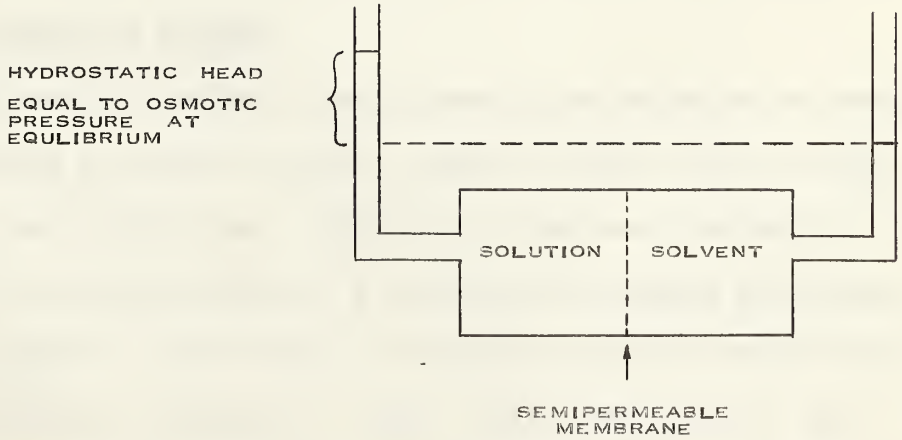


FIGURE D1 . – MEASUREMENT OF OSMOTIC PRESSURE .

Van't Hoff, in 1885, was the first to notice the similarity of the osmotic properties of solutions to the properties of gases and proposed the following equation, which proved to apply at least approximately for dilure solutions:

$$PV = nRT$$

where P is the osmotic pressure in atmospheres, V is the volume of solution which is occupied by n moles of solute, n is the number of moles of solute, R is the universal gas constant and T the absolute temperature.

If the concentration C of a solution is expressed in moles per liter (molarity), Can't Hoff's law can be re-written as:

$$P = RT\,c$$

The osmotic pressure is a colligative property of a solution, that means a property that depends only on the number of molecular particles present and does not depend on their chemical nature. Other important colligative properties of solutions are the vapor-pressure lowering, the boiling point elevation and the freezing-point lowering.

b. The Concept of Activity

The osmotic pressure of more concentrated solutions as measured in a test usually is found to be lower than the ideal osmotic pressure as defined in Van't Hoff's law. Similarly it has been observed that the lowering of the vapour pressure of a solvent is not always proportional to the mole fraction of the solute, as stated in Raoult's law for ideal behaviour (see Hiller and Herber, p. 530). This phenomenon is due to interaction between the dissolved particles and the solvent. Activity is

defined as the effective concentration of a solute. The activity of a solution is less than the true concentration if there exist solute-solute attractions and more than the true concentration if there ixist solute-solvent attractions. In very dilute solutions, activities are equal to concentrations. In general, the activity a can be expressed as

$$a = f\ c$$

where c is the concentration and f called the activity coefficient.

FIG. 2 shows the variation of the activity coefficient with the concentrations for several typical strong electrolytes.

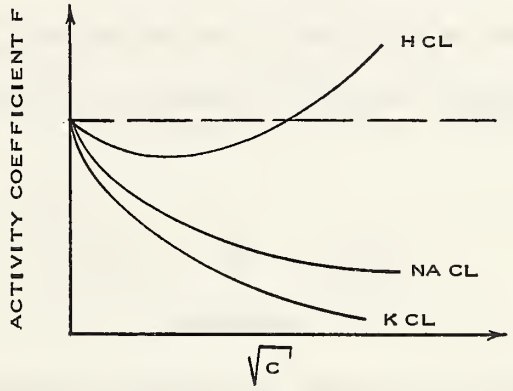


FIGURE D2. – VARIATION OF ACTIVITY WITH CONCENTRATION [FROM HILLER AND HERBER, P. 531].

Debye and Huckel were successful in calculating the activity coefficients of completely dissociated electrolytes in dilute solution by considering the electrical attractions and repulsions between ions. For uni-univalent electrolytes in water at 25°C, the following expression has been obtained:

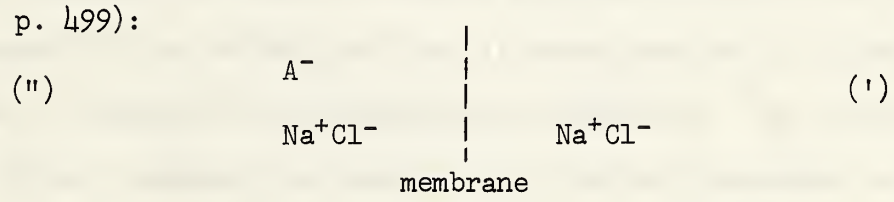
$$-\log f = 0.507\sqrt{C}$$

In their general formula, Debye and Huckel showed that in dilute solutions the activity coefficient of an ion depends only on its valence, the ionic strength[1], the dielectric constant of the medium and the temperature.

c. The Donnan Equilibrium

In investigating solutions of colloidal electrolytes, Donnan found it necessary to distinguish between the total osmotic pressure which would be obtained with a membrane impermeable to both salt and colloid and the colloid osmotic pressure which is obtained with a membrane permeable to salt ions, but not to the colloid.

Let us consider the case, where a membrane, permeable to salt ions only, separates a pure solution of NaCl from a mixed solution of NaCl and a colloidal ion A^-, as shown as follows (example from Daniels and Alberty, p. 499):



At equilibrium the activity of the salt (in dilute solutions equal to concentration) must be the same on both sides of the membrane. Using a single prime to designate the pure NaCl solution at the right and a double prime to designate the colloidal electrolyte and the salt we obtain,

$$C''_{NaCl} = C'_{NaCl} = C''_{Na^+} \times C''_{Cl^-} = C'_{Na^+} \times C'_{Cl^-}$$

Furthermore, the solutions on both sides must be electrically neutral:

---

1) for definition see Daniels and Alberty, p. 482.

$$C''_{Na^+} = C''_{Cl^-} \times C''_{A^-} \quad \text{and} \quad C'_{Na^+} = C'_{Cl^-}$$

Combinations of the above equations gives the salt distribution at equilibrium,

$$\left(\frac{C'_{Cl^-}}{C''_{Cl^-}}\right)^2 = 1 + \left(\frac{C''_{A^-}}{C''_{Cl^-}}\right)$$

d. Osmosis without Membrane

In the simple case of a solution and a solvent, as illustrated in FIG. 1, the molecular particles of the solute were held back by the semipermeable membrane. The flow of solvent from the solvent side of the membrane to the solution side of the membrane gave rise to the osmotic pressure. However, an osmotic pressure would be developed also when the free movement of the solute particles is restricted not by a membrane but by forces of adsorption and electrostatic attraction. The concept of osmosis without membrane has been found of special importance for the water retention, consolidation and swelling of clay soils (Mattson, 1932, and Ruiz, 1962).

2. Theory of Ruiz (1962)

Ruiz applies the concept of osmosis without membrane to a salt free clay soil-water system at a moisture content between the liquid and plastic limit with the following simplifications and assumptions:

1. The water occupying the free spaces between the solid particles acts as a dispersion medium (solvent) for the exchange cations.

2. The exchangeable cations tend to distribute themselves uniformly throughout the liquid, but are subjected to electrostatic attractive forces by negative charges on the surface of the solid particles. These forces play the role of the semipermeable membrane and cause an osmotic pressure to develop.

3. Considering plane particles, it can be assumed that there is no change in concentration of the exchange cations with increasing distance up to a film thickness of the order of hundreds of molecules.

The latter statement is backed by theoretical considerations of Winterkorn (1963) amd Schmid (1950), as quoted by Ruiz. Consequently Ruiz assumes a uniform distribution of cations in the aqueous medium for the moisture range in which we are interested. For higher water contents, the cations will concentrate more towards the particle surfaces in accordance with the classical theory of the Helmholtz double layer, which is applicable for dilute clay suspensions.

Assuming a uniform concentration of the exchange ions in the soil moisture, and knowing the exchange capacity and average valence of the exchangeable cations, we are able to calculate the molar concentration and to apply Van't Hoff's law in order to determine the osmotic pressure which would be produced under ideal conditions.

The exchange capacity "T" is usually measured in milliequivalents

per 100 grams of dry soil, one milliequivalent being equal to 1/1000 equivalent. The number of moles per 100 grams of soil therefore is equal to "T"/1000 x Va, when Va represents the valency. This number of moles is present in w grams of pore water per 100 grams of soil at a moisture content of w%. The concentration C of exchange ions in the aqueous dispersion medium, expressed in moles per liter, therefore is:

$$C = \frac{\frac{"T"}{1000\ Va}}{w}\ 1000 = \frac{"T"}{w\ Va}$$

Under ideal conditions, a solution of this concentration, separated from pure water by a semipermeable membrane, would give rise to an osmotic pressure (Po) ideal, which is according to Van't Hoff

$$(Po)_{ideal} = RT\ \frac{"T"}{w\ Va}$$

The real osmotic pressure, designated as $(Po)_{real}$, will not be equal to $(Po)_{ideal}$, mainly because the exchangeable cations are not freely movable but attracted to the clay particles. This effect decreases the kinetic energy of the cations and thereby their diffusion tendency. $(Po)_{real}$ is expected to be smaller than $(Po)_{ideal}$ and one may write

$$(Po)_{real} = (Po)_{ideal} \times f$$

where f is a coefficient smaller than 1 and corresponds to the activity factor defined previously for electrolytic solutions.

As pointed out by Ruiz, the coefficient of activity f must decrease with decreasing moisture content, since the restraining electric attraction of the cations by the charged particle surfaces increases with increasing proximity of the cations, i.e. with decreasing moisture content.

Therefore f should be expressed as a function of the moisture content f (w) and we should write

$$(Po)_{real} = RT \frac{"T"}{wVa} \times f(w)$$

Interpretation of this formula shows, that the real osmotic pressure $(Po)_{real}$ in a soil water system depends upon the following variables.

1. Temperature T,
2. Characteristics of the exchange complex, represented by the exchange capacity "T" and valence Va of the cations.
3. The moisture content w measuring dilution of the cations, and
4. The activity coefficient f(w), expected to vary with varying moisture content.

As an example, let us compute the osmotic pressure which would be developed under ideal conditions in a Lake Edmonton clay with the following characteristics.

Total exchange capacity "T" = 25 me/100 grams
Average valence of cations Va = 2
Moisture content w = 40%
Temperature T = 273 + 25 = 298K°

R is the gas constant and equal to 0.082 liter atm deg/mole.

Thus we obtain

$$(Po)_{ideal} = 0.082 \times 298 \ \frac{25}{40 \times 2} = 7.63 \text{ atm.} = 7.87 \text{ kg/cm}^2$$

If one would be able to measure $(Po)_{real}$ in a soil water system, then the activity factor f(w) could be calculated. As stated by Ruiz, the logical way of determining $(Po)_{real}$ is by means of the consolidation test as used in soil mechanics. The applied external load P in the consolidation test corresponds to the hydraulic head measured in an osmometer. Under any applied pressure, water is squeezed out of the consolidation test sample until an equilibrium moisture content is reached, related to a certain ion concentration. E.g. in a consolidation test on Edmonton clay, a moisture content of 40% is reached under a load of 5 kg/cm^2. Thus we obtain the activity factor as

$$f(w) = \frac{P}{(Po)_{ideal}}$$

$$f(40\%) = \frac{5}{7.63} = 0.635$$

3. Theory of Bolt (1956)

In his physico-chemical analysis of the compressibility of pure clays, Bolt makes the following assumptions:

1. All clay particles are oriented parallel to each other and packed as closely as the osmotic forces permit.

2. The double layer theory (Gouy, 1910), describing the concentration of exchangeable cations around

negatively charged clay particles, is valid.

3. Van't Hoff's law can be used in calculating the osmotic pressure of a clay system in equilibrium with an electrolyte solution. The semipermeable membrane is formed by the clay particles themselves, while the solvent is provided by the solution which is pressed out upon loading of the clay specimen.

4. The distance between clay plates can be calculated from density, specific surface and void ratio of the clay.

Bolt himself considers assumption (4) the most uncertain, since the clay might not contain perfectly flat particles.

Van't Hoff's equation is believed to introduce an error of not more than 10%. In Bolt's previous investigations, the Gouy theory was found definitely satisfactory for pure clays. The assumption of parallel alignment of the clay plates, as accepted by Bolt, later was heavily criticized by Terzaghi (1956), who put forward the cluster concept of clay structures: clusters of clay mineral particles form minute osmotic cells, whose size and compressibility are determined by chemical factors.

List of References of APPENDIX D

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